VOL. 6. FEBRUARY, 1952 No. 1

WELDING RESEARCH

PRICE FIVE SHILLINGS

Published by
BRITISH WELDING RESEARCH ASSOCIATION · 29 PARK CRESCENT · LONDON · W.1

WELDING RESEARCH

VOL. 6 NO. 1 FEBRUARY, 1952

Published by

BRITISH WELDING RESEARCH ASSOCIATION

Head Office and Metallurgical Laboratory

29, PARK CRESCENT, LONDON, W.1

Telephone: Langham 7485/9

Telegrams: Weldaserch, Wesdo, London

Research Station

Abington Hall, Abington, nr. Cambridge

Telephone: Linton 375

Telegrams: Weldaserch, Cambridge

Director of Research

H. G. TAYLOR,
D.SC.(ENG.), D.I.C., M.I.E.E., F.INST.P.

Secretary

A. O'NEILL, B.SC.(ECON.), A.C.I.S.

Editor and Publications Officer

J. H. GAMESON

CONTENTS

Page

Correlation of Weldability Tests with Structural Joints, Part I 2*r*

The Weldability and Weld Strength of some Magnesium Alloy Sheet Materials 13*r*

A New Double-Fillet Test for Hot-Cracking .. 27*r*

R.76

CORRELATION OF WELDABILITY TESTS WITH STRUCTURAL JOINTS

Part I.—Investigations with Tests of the Restrained Fillet Type.

This is the first of three reports on an investigation undertaken by the British Welding Research Association to produce a test for hard zone cracking in arc-welded low alloy steel. Parts II and III will describe experiments made with unrestrained fillets, structural joints and the C.T.S. (Controlled Thermal Severity) test.

Various tests were examined and compared with structural joints, rate of cooling in the hard zone being used as a basis for comparison. The results indicated a relationship, when using a given steel and electrode, between rate of cooling at 300 deg. C. in the hard zone and incidence of hard zone cracking. A weldability test was devised having known grades of thermal severity covering the range obtained in structural joints.

This new weldability test, the C.T.S. test, is used to derive an empirical equation which relates rate of cooling in the hard zone to fillet size (single run) and geometry of the welded joint. A weldability index is proposed, based on the C.T.S. test, for classifying low alloy steels according to their liability to hard zone cracking, taking into account the type of electrode used.

By C. L. M. Cottrell, M.Sc., and P. H. R. Lane, B.Sc. (Eng.)

SYNOPSIS

The report describes the initial stages of an investigation into the production of a weldability test or tests giving results comparable to those obtained in any given structural joint. The work has been carried out mainly with a low alloy manganese-molybdenum steel, but some tests have been made on a carbon-manganese steel for comparison.

The Reeve fillet weld cracking test has been taken as the starting point of this investigation. Other tests used include the miniature Reeve and various modifications of both this test and the full Reeve. The weldability tests have been compared using the cooling rate in the hard zone as a criterion. Some fundamental considerations of heat flow have been taken into account in comparing the tests and these considerations have served as a guide for further investigations.

Two different types of electrode have been compared from the standpoint of their ability to weld the manganese-molybdenum steel without failure due to hard zone cracking.

INTRODUCTION

This investigation has been undertaken with a view to determining the conditions under which sound welds can be made in a structure fabricated from a low alloy manganese-molybdenum steel having a yield strength (0·3 per cent. proof stress) of 27 tons per sq in.

The type of failure which often occurs in welded joints in alloy steel is known as hard zone cracking or cold cracking. These cracks occur in the hardened zone of the plate material adjacent to the fusion line.

It has been suggested by Hopkin[1] that hydrogen, which is dissolved in the weld metal, is a contributory cause of hard zone cracking. The relative effects of joint rigidity and rate of cooling on the initiation of hard zone cracking have not been fully understood, and the most satisfactory weldability test at present used incorporates maximum restraint combined with fast rates of cooling. This test is known as the Reeve[2] fillet weld cracking test. The inability to differentiate between the two factors joint rigidity and cooling rate has been a serious difficulty in attempts to modify the Reeve test. In the past the general view has been that it would be safer to retain test conditions which are more severe than those found in practice, rather than to accept a test that would classify as weldable a steel which might give difficulties in industry.

In this initial investigation the effect of rate of cooling on the initiation of hard zone cracking has been studied in an attempt to provide a scientific basis for the correlation of weldability tests and structural joints. The tests available at the start of the investigation were the Reeve, the modified Reeve[3] and the miniature Reeve test. Modifications of these existing tests were also used.

MATERIALS

The steels used in the investigation were a manganese-molybdenum and a carbon-manganese steel. Both steels were supplied in the as-rolled condition in the form of plates. The cast analyses of the steels were supplied by the manufacturers and are given in Table I with average hardness values for the plates in the normalised condition.

Table I.—Cast Analyses and Hardness Values

Steel Type	Plate Thickness (inches)	C %	Si %	S %	P %	Mn %	Ni %	Cr %	Mo %	Average Hardness as-normalised (V.P.N. 10 kg. load)
Mn-Mo	1	0·17	0·16	0·027	0·024	1·24	0·55	0·195	0·26	195
	1	0·165	0·16	0·043	0·037	1·26	0·47	0·10	0·275	203
	1	0·16	0·15	0·019	0·023	1·22	0·37	0·15	0·24	197
C-Mn	1	0·23	0·07	0·028	0·025	1·56	0·22	0·09	0·03	204

The plates were normalised by heating at 900 deg. C. for ¼, ½ and 1 hour for ¼, ½ and 1 in. thickness respectively, followed by cooling in still air. Welding tests were made on the plate material after normalising and with the surfaces machined.

The arc welding electrodes used in the tests are given in Table II.

Table II

B.E.A.M.A.-I.O.W. Classification	Type of Coating	Sizes Used
E 217	Rutile	10, 8, 6 and 4 s.w.g.
E 317	Rutile basic	10 and 8 s.w.g.

The electrodes for all tests were baked at 110 deg. C. for a minimum time of one hour immediately prior to making the test welds. This treatment was carried out in order to ensure that the moisture content (potential hydrogen) of each type of electrode was maintained at a constant low value.

INVESTIGATIONS WITH RESTRAINED TESTS AT PRESENT IN USE

Modified Full Reeve Test

The Reeve test was first modified by Dearden and O'Neill[3] to incorporate two test welds instead of one. This modification was used because it effected a considerable economy in material. The test consisted of two plates of the steel under test bolted to a 2½ in. thick mild steel base plate. The top plate was 6 in. sq. and the bottom plate 12 by 7 in., both plates being of 1 in. thick material. A diagram of the test assembly is shown in Fig. 1. The contact surfaces between all the plates were surface ground in order to ensure good thermal contact which would give uniform heat flow conditions in all tests. The edges of the top plate were machined.

The test plates were tightly bolted using ⅞ in. diameter mild steel bolts to a 16 by 12 by 2½ in. base plate which could be tilted at an angle of up to 45 deg. to the horizontal. Anchor welds were made on two opposite sides of the top plate as indicated in Fig. 1. Each anchor weld consisted of three runs made in the horizontal position using a 6 s.w.g. class E.217 electrode and a welding current of 210 amp. The plates were then allowed to cool to room temperature, the clamping bolts tested and any slackness taken up.

The test assembly was then tilted to an angle of 45 deg. to the horizontal in one direction for the first test weld and in the other direction for the second test weld.

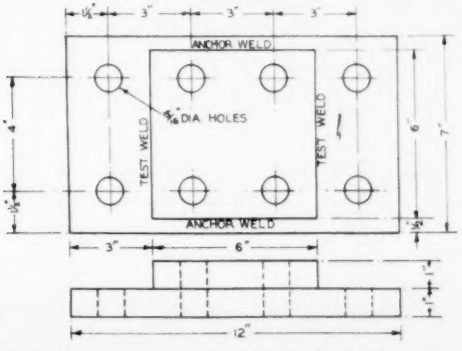


Fig. 1. Dimensions of plates used for modified full Reeve test.

Miniature Reeve Test

The miniature Reeve test consisted of two plates of the steel under test bolted together with a single bolt. The top plate was 3 by 1¼ in. and the bottom plate 4 by 3¼ in., both plates being of the same thickness, namely, ¼, ½ and 1 in., depending upon the thickness of plate tested. A diagram of the test is given in Fig. 2. The lower surface of the top plate and the upper surface of the bottom plate were surface ground, to ensure uniform heat flow conditions in all tests. The edges of the top plate were machined.

The test plates were tightly bolted together using a ½ in. diameter mild steel bolt. Anchor welds were made round three edges of the top plate as indicated in Fig. 2. Each anchor weld consisted of three runs made in the horizontal position using a class E.217 electrode, the size of electrode and welding current being 6 s.w.g. (210 amps.), 8 s.w.g. (170 amps.) and 10 s.w.g. (125 amps.) for 1, ½ and ¼ in. thick plates respectively. The plates were then allowed to cool to room temperature, the clamping bolt tested and any slackness taken up.

Each test assembly was then placed on a cemented asbestos board inclined at an angle of 45 deg. to the horizontal and held in position by clips, as shown in Fig. 3, for the deposition of the test weld.

Determination of Cooling Rates

Measurements of temperature changes were made on every test weld using a chromel-alumel thermocouple inserted into the plates under test. It was thought that the best position for the measurements of cooling rate would be in the heat affected zone as near as possible to the fusion line. The hot junction of the thermocouple was, therefore, placed in the heat affected zone midway along the horizontal leg of the fillet weld and near to the fusion line of the weld bead. The distance of the thermocouple from the upper surface of the bottom plate, and from the root of the weld was determined by measurements made on microsections cut from previous experimental fillet welds.

A blind hole was drilled from the underside of the bottom plate to accommodate the thermocouple. After drilling to the required depth the end of this hole was machined flat by means of a specially ground twist drill. In order to increase the efficiency of heat transfer to the thermocouple, a small disc of soft copper 0·015 in. thick was hammered into the end of the thermocouple hole. Thermal contact between the

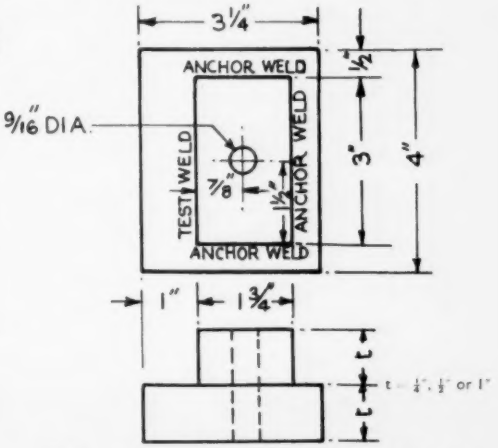


Fig. 2. Dimensions of plates used for miniature Reeve test.

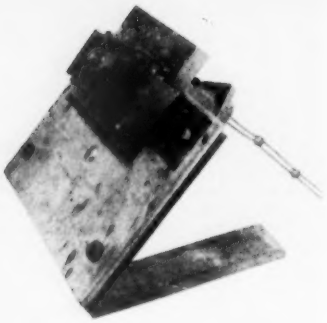


Fig. 3. Miniature Reeve test mounted on heat insulating stand. Test with half inch thick plate.

Fig. 4. Method of attaching thermocouple to miniature Reeve test. One inch thick plate.

thermocouple bead and the copper was assisted by grinding a flat on the end of the bend.

The thermocouple wires were passed through twin bore alumina sheathing and the whole assembly was pressed firmly into the thermocouple hole so that the hot junction was in good contact with the copper disc. The method of attaching the thermocouple assembly to the miniature Reeve test is shown in Fig. 4, pressure being exerted on the thermocouple assembly by means of a screwed brass bush, bearing on the twin bore sheathing. Temperatures were measured and recorded on a strip-chart recorder modified to print every five seconds, with the chart travelling at 30 mm. per minute. The instrument was also modified to give a full-scale deflection with an input of 30 mv. corresponding to a temperature of 740 deg. C., this temperature being occasionally exceeded for short periods, usually five seconds or less. The thermocouple was connected through a cold junction to the recording instrument.

Welding Conditions

Alternating current with an open circuit voltage of 80 volts was used for the test welds; the conditions for the tests are given in Table III. The weldability tests used were the full Reeve on 1 in. thick plate and the miniature Reeve on 1, ½ and ¼ in. thick plate.

In most of the tests four gauges of electrode were used giving four different fillet sizes with each variation of plate thickness. A nominal deposition ratio of 1½ in. of electrode per 1 in. of test weld was used, the welds being 6 in. and 3 in. long respectively for the full and miniature Reeve tests. In the miniature Reeve tests on 1 in. thick plate an extra large fillet size was deposited with the 4 s.w.g. electrode by using a greater deposition ratio, in addition to the normal size fillet, in an attempt to prevent hard zone cracking. Only three different fillet sizes were deposited, using the miniature

Table III. Welding Conditions for Miniature and Full Reeve Tests

Test Assembly	Steel	Plate Thickness (Inches)	Electrode		Welding Current (amp.)	Energy Input (Joules/in. $\times 10^{-3}$)	Approx. Fillet Size (Inches)
			Class	s.w.g.			
Modified Full Reeve	Mn-Mo	1	E.217	10	127	17	3/16
				8	173	28	¼
				6	210	38	9/32
				4	295	69	13/32
Miniature Reeve	Mn-Mo	1	E.217	10	124	15	3/16
				8	171	26	¼
				6	206	38	9/32
				4	300	68	13/32
				4	310	79	7/16
Miniature Reeve	C-Mn	½	E.217	10	127	18	3/16
				8	172	25	¼
				6	213	40	5/16
				4	305	71	13/32
Miniature Reeve	Mn-Mo	½	E.217	10	127	17	3/16
				8	172	26	¼
				6	213	40	9/32
				4	300	70	13/32
Miniature Reeve	Mn-Mo	½	E.317	10	117	19	3/16
				8	159	29	¼
Miniature Reeve	Mn-Mo	¼	E.217	10	122	11	5/32
				10	128	19	3/16
				8	173	30	¼

Reeve test on ¾ in. thick plate and one of these was of extra small size made with a 10 s.w.g. electrode.

The full set of miniature and full Reeve tests was made using Mn-Mo steel and a class E.217 electrode and a few extra tests were made on the ¾ in. miniature Reeve assembly using Mn-Mo steel and class E.317 electrodes and also using a carbon manganese steel and E.217 electrodes.

The welding current was measured by means of a current transformer and moving iron ammeter, the arc energy being measured by a dynamometer type wattmeter.

Examination of Test Welds

All tests were left for a week before sectioning after which time the test welds were cut out by making cuts parallel to the welding direction by means of a power hack-saw. Each weld was then sectioned in three places, at the centre and 1½ in. on each side of the centre for the full Reeve tests, sections being taken closer together for the miniature Reeve test, namely, at the centre and ¾ in. on each side.

The sections were then micro-polished, etched in a solution of 3 per cent. picral with 3 per cent. hydrochloric acid and examined microscopically for cracks. The microscopic examination was made at a magnification of about 400 diameters, special attention being paid to the hard zone adjacent to the fusion line. Crack lengths were then measured on the screen of a projection microscope adjusted to give an accurate magnification of 250 diameters, and these lengths were reported as a percentage of the total leg length. Hardness surveys were made on the centre section from each test weld as shown in Fig. 5, with a diamond pyramid indenter and 10 kg. load.

Results and Discussion

It was observed with the tests on 1 in. thick plate that the full Reeve test is more severe than the miniature test as estimated by the extent of hard zone cracking, this effect being shown in Table IV. On plates less than 1 in. thick this effect will be greatly accentuated.

From the results of miniature Reeve tests on ¾ in. thick plates it has been shown that the Mn-Mo steel has better weldability than the C-Mn steel. This may be due in part to the lower hardenability of the Mn-Mo steel, as shown in Table V. This result indicates that better weldability is obtained in high tensile steels by using alloying elements in addition to carbon and manganese, thus enabling the contents of carbon and manganese to be reduced. The beneficial effect of molybdenum additions in steels of the Mn-Mo type has been fully described by Barr[4] in a recent paper.

Class E.317 electrodes have given better weldability than class E.217 on the Mn-Mo steel. The difference in weldability observed between the two types of electrode is quite important, and this effect will be dealt with more fully in the next report on this investigation. These results are shown in Table V together with the data for the miniature Reeve tests on ¾-in plate.

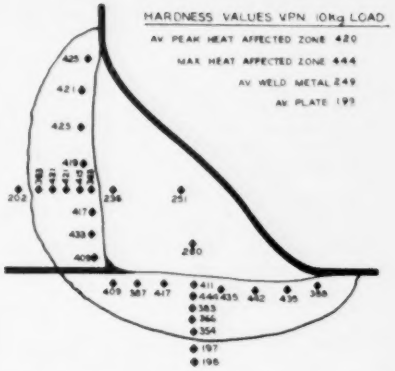


Fig. 5. Hardness survey diagram of centre section of test weld, modified full Reeve test on 1 in. thick plates. Mn-Mo Steel. 6 s.w.g. Electrodes class E.217.

When these results were obtained it appeared that, whereas the miniature Reeve tests probably did not give conditions as severe as those obtaining in practice, the full Reeve test represented the maximum possible severity. It was agreed that the restraint in the full Reeve assembly was likely to be greater than that present in the miniature test, but at the same time the cooling conditions were markedly different at lower temperatures. This difference in rate of cooling is seen by comparing Figs. 6 and 7, in which the square root of the rate of cooling in the hard zone is plotted against the temperature in that zone for the full and miniature Reeve tests on 1 in. thick plates respectively. It was apparent from the negligible differences in average peak hardness values for the miniature and full Reeve tests given in Table IV, that the rates of cooling at temperatures above 500 deg. C. were not very different for a given fillet size on each type of test since it is the cooling rate at these higher temperatures which controls the degree of hardening of the steel. The fact that the cooling rates in the hard zone for equivalent fillet sizes on the miniature and full Reeve tests were not very different at temperatures over 500 deg. C. was also indicated by the form of the square root rate of cooling curves shown in Figs. 6 and 7.

It is interesting to note that the square root cooling rate curves for the full Reeve test are in fair agreement with a theory proposed by Rosenthal[5] for heat flow in welds. Rosenthal considered only the case for a weld with an infinite heat sink and assumed a quasi-stationary state around the welding arc.

Table IV.—Hardness and Cracking Data for Miniature and Full Reeve Tests on 1 in. Plate. Steel Mn-Mo, Electrode Class E.217

Test Assembly	Approx. Fillet Size (Inches)	Energy Input (Joules/in. × 10^{-3})	Average Hardness (V.P.N. 10 kg. load)		Hard Zone Cracking (per cent. leg length)
			Peak Hard Zone	Weld Metal	
Modified Full Reeve	3/16	17	426	269	35
	¼	28	419	256	31
	9/32	38	420	249	22
	13/32	69	396	241	24
Miniature Reeve	3/16	15	431	289	30
	¼	26	430	259	37
	9/32	38	429	254	22
	13/32	68	387	250	8
	7/16	79	365	213	borderline

The equation given by Rosenthal is as follows:

$$\frac{dt}{ds} = \frac{2\pi k v}{Q_v}(t - t_o)^2 \quad \ldots \quad (1)$$

where t = temperature of the point where rate of cooling is assessed in degrees C.
t_o = initial temperature of plate in degrees C.
s = time in seconds.
k = thermal conductivity of the metal in C.G.S. units.
v = rate of welding in cm./sec.
Q_v = heat input in cal./sec.

For a given heat input and welding speed this equation reduces to:

$$\frac{dt}{ds} \propto (t - t_o)^2 \quad \ldots \quad (2)$$

Since the initial plate temperature is also constant, then:

$$\frac{dt}{ds} \propto t^2,$$

or,

$$\sqrt{\frac{dt}{ds}} \propto t \quad \ldots \quad (3)$$

This equation indicates that for a given infinite plate the square root of the rate of cooling at a point should be proportional to the temperature of the point. This theoretical consideration is supported by the results of tests with the full Reeve assembly given in Fig. 6. In this figure the square root rate of cooling curves are in fact straight lines which intersect the temperature axis at the initial plate temperature (20 deg. C.).

It will be observed from Fig. 6 that the slope of the square root rate curves becomes greater as the energy input value is increased. The slope of these curves from theoretical consideration should be as follows:

$$\frac{t - t_o}{\sqrt{\frac{dt}{ds}}} \quad \sqrt{\frac{Q_v}{2\pi k v}} \quad \sqrt{\frac{J_v}{67k}} \quad \ldots \quad (4)$$

where J_v = heat input in Joules/in.

By substituting the observed values for heat input in this equation the slopes of the root rate curves for the full Reeve test may be calculated theoretically, and then compared with the values obtained from the cooling curves.

In order to make this substitution it is necessary to know what proportion of the total energy liberated in the arc goes

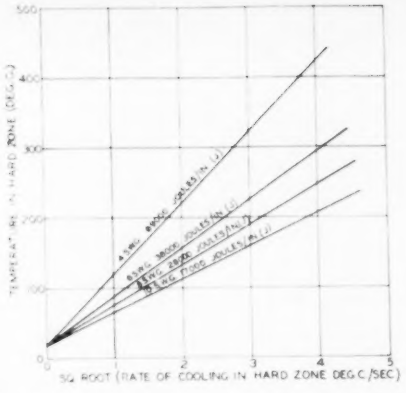

TEMPERATURE IN HARD ZONE (DEG.C.)
SQ. ROOT (RATE OF COOLING IN HARD ZONE DEG.C./SEC.)
4 SWG. 89000 JOULES/IN. (J)
6 SWG. 38000 JOULES/IN. (J)
8 SWG. 28000 JOULES/IN. (J)
10 SWG. 17000 JOULES/IN. (J)

Fig. 6. Square root cooling rate curves, modified full Reeve test on 1 in. thick plates. Mn-Mo steel. Electrodes class E.217.

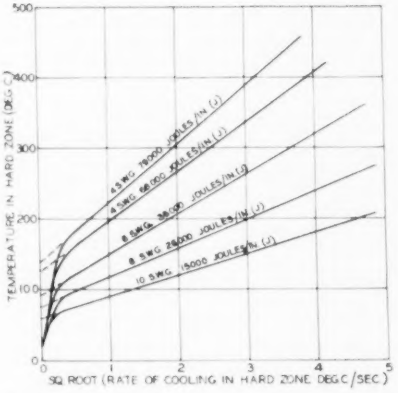

TEMPERATURE IN HARD ZONE (DEG.C.)
SQ. ROOT (RATE OF COOLING IN HARD ZONE DEG.C./SEC.)
4.5 SWG. 78000 JOULES/IN. (J)
4 SWG. 68000 JOULES/IN. (J)
6 SWG. 38000 JOULES/IN. (J)
8 SWG. 28000 JOULES/IN. (J)
10 SWG. 19000 JOULES/IN. (J)

Fig. 7. Square root cooling rate curves, miniature Reeve test on 1 in. thick plates. Mn-Mo steel. Electrodes class E.217.

Table V. Hardness and Cracking Data for Miniature Reeve Test

Steel	Plate Thickness (Inches)	Electrode Class	Approx. Fillet Size (Inches)	Energy Input (Joules/in. $\times 10^{-3}$)	Average Hardness (V.P.N. 10 kg. load)		Hard Zone Cracking (per cent Leg Length)
					Peak Hard Zone	Weld Metal	
C-Mn	1	E.217	3/16	18	497	303	34
			1/4	25	470	270	32
			5/16	40	402	237	2½
			13/32	71	309	211	Nil
Mn-Mo	1	E.217	3/16	17	432	283	36
			1/4	26	419	244	7
			9/32	40	393	226	Nil
			13/32	70	313	215	Nil
Mn-Mo	1	E.317	3/16	19	427	257	15
			1/4	29	417	246	Nil
Mn-Mn	1	E.217	5/32	11	408	282	9
			3/16	19	374	254	Nil
			1/4	30	316	231	Nil

into the weld, the remainder being lost by radiation and other means. Rosenthal gave a figure of 65 per cent. for the proportion of energy going into the weld. However, this figure seemed rather low, and for this reason a series of calorimetric tests was carried out for verification. The results of these tests are given in Table VI, and it will be observed that the smaller the electrode the greater the proportion of the total energy going into the weld; this effect is probably due to the increased spatter loss with larger rods.

Table VI. Percentage of Total Heat which goes into the Weld

Electrode Size (s.w.g.)	$\frac{J_v \times 100}{J}$ *
10	88
8	86
6	82
4	79

* J = total energy liberated in the arc in Joules/in.

It is also necessary to obtain a value for k in order to complete the substitution and this value has been taken as 0·10 C.G.S. units for the steel used.

The results of the calculated and observed slopes for the square root rate curves in the full Reeve test are given in Table VII. There is good agreement between the calculated and observed values, the greatest difference being only 9 per cent. on the weld made with the 4 s.w.g. electrode. This is quite satisfactory since the calorimetric experiments showed that the ratio J_v/J, obtained from a number of tests with a 4 s.w.g. electrode, was rather variable.

These results indicate that the full Reeve test gives a good approximation to an infinite heat sink where metal arc welding is concerned, and for this reason the test should give thermal conditions as severe as any which may be found in practice.

The results obtained from the miniature Reeve test show that unlike the full Reeve test, it does not act as an infinite heat sink. This is quite understandable from the size relationship of the two tests. The difference between the two tests from the standpoint of cooling rate at various temperatures can be observed from a comparison of Figs. 6 and 7. It was thought that the square root rate of cooling curves for the miniature Reeve test might conform to the Rosenthal theory at high temperatures where the effect of the restricted heat sink would not be likely to affect the cooling rate. However, in these tests, the method used for measuring temperature was not capable of accurately recording fast rates of change, and for this reason all readings at temperatures above 500 deg. C. for the large welds and above 300 deg. C. for the small welds were subject to error. Therefore, it was not possible to observe the slope of the square root cooling rate curves for the miniature Reeve test at high temperatures.

It will be observed from Fig. 7 that the general slope of the square root cooling rate curves for the miniature Reeve test is less than that obtained for the full Reeve test. This difference in slope is due to the restricted heat flow in the miniature test. The heat energy transferred to the assembly during the welding process is sufficient to raise considerably the temperature of the whole assembly. This complete heat saturation of the test assembly is reflected in the square root cooling rate curves and is indicated by the transition from the general slope to a much steeper slope.

The steeper slope indicates cooling of the test assembly as a whole, mainly by convection, and obeys a fourth root relationship with temperature.

The temperature at which the linear part of the square root cooling rate curve would meet the temperature axis may be calculated by using the following equation:

$$t' - t_0 = \frac{H}{cw} \quad . \quad . \quad . \quad . \quad (5)$$

where t' = temperature to which the test assembly rises in degrees C.
t_0 = initial temperature of the assembly in degrees C.
c = specific heat of the metal in calories per gram.
w = weight of the test assembly in grams.
H = heat input to the test assembly in calories.

The calculated and observed values for the rise in temperature of the miniature Reeve test are given in Table VIII. It will be observed that the calculated values of temperature rise are generally higher than the values observed from the square root cooling rate curves. This is probably due mainly to loss of heat by radiation and convection from the test assemblies at the higher temperatures. This is substantiated by the fact that with higher values of heat input, where the temperature rise is greater, the difference between calculated and observed values is greater.

The rise in temperature of the miniature Reeve test assembly is more pronounced with thinner plates, this effect being shown in Figs. 8 and 9 where the deviation from linearity of the square root cooling rate curves can be observed. Fig. 10 gives square root rate of cooling curves for a weld made with an 8 s.w.g. electrode, and this diagram indicates that the different temperatures to which the test assemblies rise depend on the plate thickness. Also the rates of cooling in the 100 deg. C. to 500 deg. C. region vary greatly, being much more rapid with the thicker plates. It is probable that with ¼-in. plates the Rosenthal equation is never satisfied since saturation of the plate thickness is approached while the hard zone is still in the high temperature region. It should be noted in Fig. 10 that the energy input values are not strictly comparable, and this has altered slightly the spacing of the curves; the general relation is, however, unchanged.

In order to provide further evidence of the temperature rise of the miniature Reeve assemblies, the temperature at the edge of the bottom plate remote from the test weld was measured in a number of the tests. These temperatures were measured at intervals and are shown plotted against the temperature in the hard zone in Fig. 11. These curves have been extrapolated to meet the ideal cooling curve where the

Table VII.—Relation between Calculated and Observed Slopes of Square Root Rate of Cooling Curves from Full Reeve Tests (Steel Mn-Mo)

Electrode Type E.217 Size (s.w.g.)	J (Joules/in.)	J_v (Joules/in.)	Calculated Slope $\sqrt{\frac{J_v}{67k}}$ taking $k = 0{\cdot}10$	Observed Slope
10	17,000	15,000	47	47
8	28,000	24,000	60	57
6	38,000	31,000	68	69
4	69,000	55,000	91	100

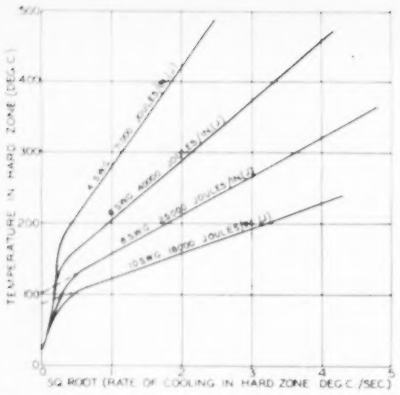


Fig. 8. Square root cooling rate curves, miniature Reeve test on ½ in. thick plates. Steel C-Mn. Electrodes class E.217.

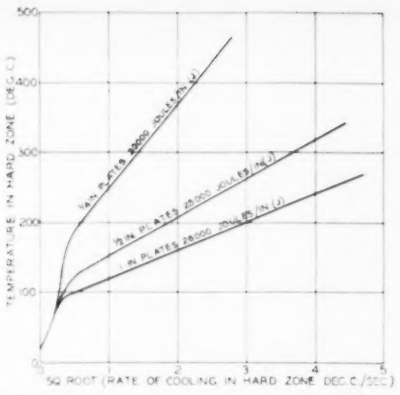


Fig. 10. Square root cooling rate curves, miniature Reeve test. 8 s.w.g. Electrodes class E.217.

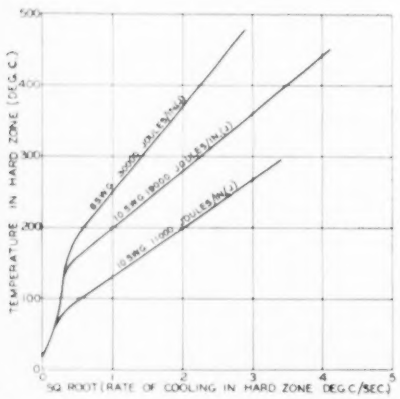


Fig. 9. Square root cooling rate curves, miniature Reeve test on ¾ in. thick plates. Mn-Mo steel. Electrodes class E.217.

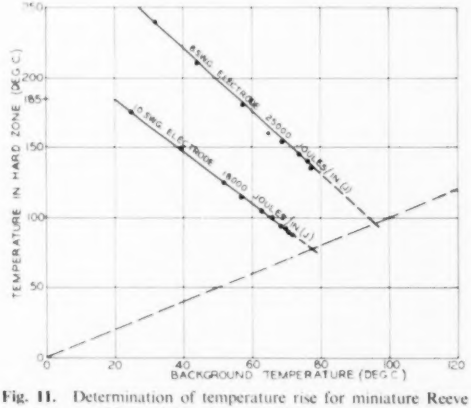


Fig. 11. Determination of temperature rise for miniature Reeve test assembly on ½ in. plates. Mn-Mo steel. Electrodes class E.217.

Table VIII. Calculated and Observed Values for Temperature Rise of Miniature Reeve Test on ½ in. Mn-Mo Steel

Electrode Type E.217 Size (s.w.g.)	Heat Input (Joules)	Calculated Temperature (deg. C.) $(T = \frac{H}{C \cdot W} + 20)$	Observed Temperature from Sq. Root Cooling Rate Curve
4	180,000	189	140
4	155,000	167	126
6	93,000	108	93
8	67,000	84	77
10	39,000	58	60

Table IX. Calculated Temperature to which Miniature Reeve Test Assembly Rises. Mn-Mo Steel ½ in. Plates, Electrode Type E.217

Electrode Size (s.w.g.)	Fillet Size (Inches)	Calculated Temperature (deg. C.)		Temperature below which Cooling Rate will be affected (deg. C.)*
		From Background Temperature Curves	From Square Root Cooling Rate Curves	
10	3/16	77	86	185
8	¼	96	102	265

* See Fig. 11.

whole assembly cools as a single mass. The point of intersection of these curves gives the average temperature rise of the assembly in each test. These values for temperature rise are in agreement with those observed from the square root cooling rate curves produced to cut the temperature axis, shown in Fig. 8. These values are given in Table IX for comparison.

The background temperature curves are of further use since they show when the restricted size of heat sink is liable to effect the cooling rate in the hard zone. Thus, the temperature of the hard zone at which the background temperature begins to rise gives an indication of the temperature below which the rate of cooling in the hard zone is liable to be affected and these values are also given in Table IX.

As a result of these experiments it was decided to investigate the possibility of increasing the thermal severity of the Miniature Reeve test by increasing the available heat sink, this being done in an effort to bring the test into line with conditions occurring in an actual structure. It was also decided to reduce the thermal severity of the full Reeve test by insulating it from the base plate, to bring the test more into line with the majority of structural joints. These further experiments are described in the next part of this report.

MODIFICATIONS OF RESTRAINED TESTS TO ALTER THERMAL CONDITIONS

The Insulated Modified Full Reeve Test

The insulated modified full Reeve test assembly was similar to the modified Reeve test described in a previous section of this report, except that a cemented asbestos board was inserted between the bottom and base plates, the test plates being of the thick Mn-Mo steel. The asbestos board was 3/16 in. thick and was firmly held between the two steel plates by means of the usual clamping bolts. This modification was made in order to remove the infinite heat sink, and at the same time retain the external restraint imposed by the rigid base plate. Anchor welds were made as described in a previous section of this report.

Modification 1 of the Miniature Reeve Test

The first modification of the miniature Reeve test was made by bolting a flat bar 4 ft. by 3 in. by ½ in. made of mild steel to the under side of the standard test assembly. A 4 in. length at the centre of the upper surface of the bar was surface ground and a 9/16 in. hole was drilled in this portion of the bar to take the clamping bolt, a photograph of the whole assembly being shown in Fig. 12. This modification of the miniature Reeve test ensured that an adequate heat sink was available, and also that heat flow to this sink was restricted by the plate section of the base plate which was made similar to that of the test plates. This restriction of heat flow was thought to be necessary in order to simulate conditions occurring in a structure. The whole assembly could be supported for welding in the horizontal position or at 45 deg. to the horizontal by means of special feet attached to the ends of the bar.

The test plates were tightly bolted to the base plate, using a ½ in. diameter mild steel bolt. Anchor welds were then made in the horizontal position along three sides of the top plate using an 8 s.w.g. class E.217 electrode. Only one thickness of the Mn-Mo steel plate was used for these tests, namely, ½ in.

Modification 2 of the Miniature Reeve Test

When experiments were made on the first modification of the miniature Reeve test it was found that bowing upwards of the edges of the bottom plate during welding impaired the thermal contact between the bottom plate and the base plate. In the second modification this bowing of the bottom plate was prevented by four ½ in. diameter bolts. These bolts passed through clearance holes in the base plate and were screwed into tapped holes in the bottom plate. The proportions of the heat sink were reduced in this instance, since it was found that the bar used in modification 1 was unnecessarily long. The dimensions of the base plate in this case were 12 by 4 by ½ in. A 4 in. length at the centre of this plate was surface ground to ensure good thermal contact with the bottom plate. A view of the whole test assembly is shown in Fig. 13, and it will be seen that feet have again been fitted to fix its position for welding.

The test plates were tightly bolted to the base plate with the five ½ in. diameter bolts, and anchor welds were made as previously described for the first modification, ½ in. thick Mn-Mo steel being used for the test plates.

Fig. 12. Modification 1. Miniature Reeve test in ½ in. thick plate.

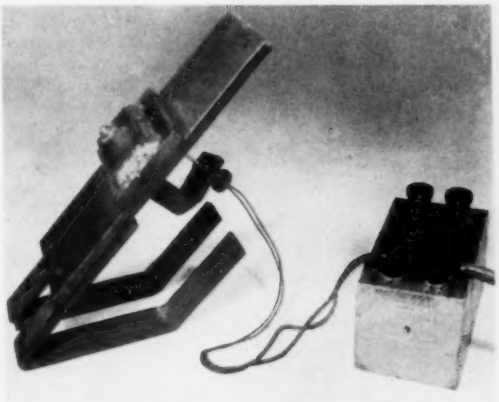


Fig. 13. Modification 2. Miniature Reeve test in ½ in. thick plate.

Test Details

Cooling curves for the tests were determined as described in a previous section of this report. A hole was drilled in the base plate of each type of test for the thermocouple wires and the thermocouple attachments can be seen in Figs. 12 and 13.

Alternating current with an open circuit voltage of 80 volts was used for all the test welds and the conditions for the tests are given in Table X.

Four separate tests of different fillet sizes were made on 1 in. thick Mn-Mo steel plate, using the insulated modified Reeve test and depositing a nominal 1½ in. of electrode per 1 in. of weld. Three different tests were made with the first modification of the miniature Reeve test and one with the second modification, using the same nominal deposition ratio. All the tests were made on the Mn-Mo steel, using E.217 type electrodes. The welding current and arc energy were measured as in the previous tests.

The examination of the test welds was carried out in a similar manner to that of the earlier tests.

Results and Discussion

The tests made using the insulated modified full Reeve test have shown that there is some departure from the condition of an infinite heat sink which applies in the case of the modified Reeve test. The effect of insulating the bottom plate from the base plate can be seen in Fig. 14, which gives square root cooling rate curves for four different weld sizes. The departure from a straight line in these curves is only slight, and it is to be expected that this type of curve would be obtained with a structural fillet joint in 1 in. thick plate. The results of hardness explorations and examinations for cracking are given in Table XI. It will be observed that the severity of hard zone cracking is similar to that obtained with the modified full Reeve test, and it appears that insulating the Reeve test has not affected the heat flow sufficiently to materially affect the hard zone cracking.

The modifications of the miniature Reeve test have both given increased cooling rates when compared with the unmodified test. The square root cooling rate curves for tests using modification 1 on ½ in. thick plates are given in Fig. 15, and it will be observed that these approach straight lines more nearly than the curves for the unmodified test which are given in Fig. 8. With the larger fillet sizes the cooling rates for the modified tests are much more rapid at all temperatures than those for the unmodified tests, but with the test having a ¼ in. fillet the rates are similar. This similarity of cooling rates between the ¼ in. test welds on the two different assemblies is, however, rather misleading since the energy supplied to the welds was different. If the energy values had been the same there is no doubt that the modified test would have given faster cooling rates. It is also to be expected that the effect of the additional heat sink in modification 1 would be to show greater differences in cooling rate from the unmodified test with larger energy input values, since the inadequacy of the

Table X.—Welding Conditions for Modifications of Reeve Tests.
Steel Mn-Mo, Electrodes Type E.217

Test Assembly	Plate Thickness (Inches)	Electrode Size (s.w.g.)	Welding Current (Amps.)	Energy Input (Joules/in. × 10⁻³)	Approximate Fillet Size (Inches)
Insulated Modified Full Reeve	1	10	125	18	3/16
		8	170	29	¼
		6	210	43	5/16
		4	305	63	13/32
Modification 1 Miniature Reeve	½	8	169	29	¼
		6	210	44	5/16
		4	30	75	7/16
Modification 2 Miniature Reeve	½	6	211	42	5/16

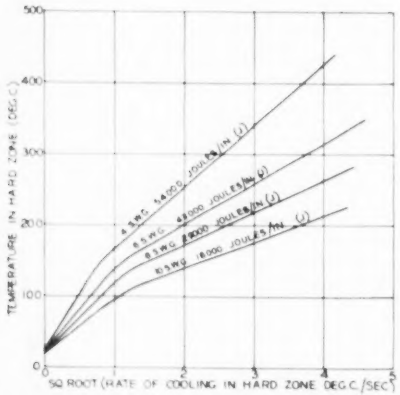


Fig. 14. Square root cooling rate curves, insulated modified full Reeve test on 1 in. thick plates. Mn-Mo steel. Electrodes class E.217.

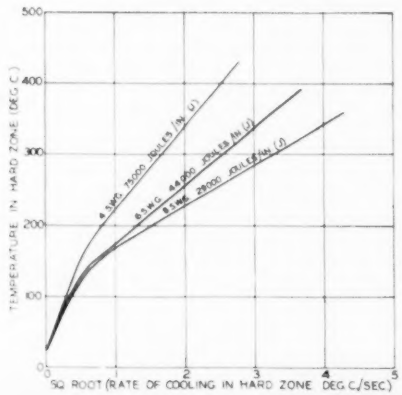


Fig. 15. Square root cooling rate curves for modified 1, miniature Reeve test on ½ in. thick plates. Mn-Mo steel. Electrodes class E.217.

heat sink with the unmodified test becomes more pronounced the greater the heat input.

The incidence of hard zone cracking and the degree of hardening in the heat affected zone for the tests are given in Table XI. It will be observed that a considerable increase in the amount of hard zone cracking has been obtained in tests using modification 1 with very little change in hardening of the heat affected zone.

Although the tests carried out on modification 1 of the miniature Reeve test gave faster cooling rates and greater amounts of hard zone cracking than the unmodified test, the new assembly was not satisfactory due to bowing upwards of the edges of the bottom plate. This bowing caused the area of contact between the bottom and base plates to be restricted to the part of the plates immediately surrounding the bolt hole. In view of the unsatisfactory nature of the thermal contact between the bottom and base plates in this modification, it was thought that reproducible conditions of heat flow would not be obtained from test to test. For this reason modification 2 was made, which ensured complete thermal contact between bottom plate and base plate.

The test made on modification 2 of the miniature Reeve test showed that although a much smaller base plate was used, faster cooling rates were obtained and the amount of hard zone cracking was increased compared with tests on modification 1. The results of hardness tests and examination for cracks on the test with modification 2 are given in Table XI, and it will be observed that, despite a considerable increase in hard zone cracking compared with the standard test, there has been no corresponding increase in hardening in the heat affected zone. The square root cooling rate curve for the test on modification 2 is shown in Fig. 16, where it is compared with curves from the standard and modification 1 tests. These curves indicate that there is a considerable difference in cooling rate at low temperatures between the three tests, which proves the inadequacy of the thermal contact in the modification 1 test.

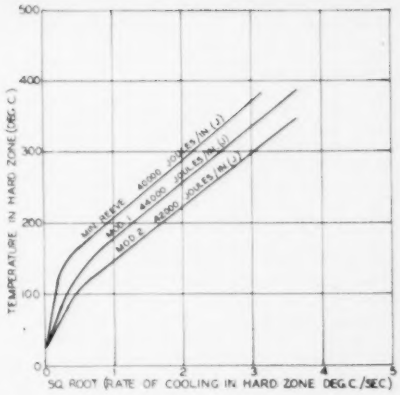


Fig. 16. Square root cooling rate curves for modifications of miniature Reeve test on ½ in. thick plates, Mn-Mo Steel. 6 S.W.6. Electrodes class E.217.

SUMMARY OF RESULTS

The results have indicated that it is possible to obtain weldability tests with thermal severities lying between those obtained with the full and miniature Reeve tests. However, of the weldability tests so far made, the most satisfactory one is the insulated full Reeve test. The modification of the miniature Reeve test showed that a base plate could not be fitted to the miniature Reeve test to give satisfactory thermal contact with the bottom plate unless a very special clamping method was used. This method of clamping by means of four extra bolts was considered to be too complicated from the point of view of a practical test. It would, therefore, appear that further research is necessary if a small weldability test with an adequate heat sink is to be developed. Meanwhile, it appears that the insulated modified Reeve test will give results which are comparable to those obtaining in a structural joint when equivalent plate thickness is used.

The relative effects of external restraint, rate of cooling and heat affected zone hardness on hard zone cracking remain to be elucidated although some interesting results have been obtained relating to rate of cooling and developed hardness in the hard zone. It has been observed in the experiments with the miniature Reeve test and its various modifications that there was very little difference between tests from the standpoint of developed hardness in the hard zone. This indicates that rates of cooling at the higher temperatures are substantially the same. However, low temperature (<400 deg. C.) cooling rates and the susceptibility to hard zone cracking were both markedly increased in the modified tests. These differences are shown in Table XII from which it can be inferred that, with the miniature Reeve test and modification 1, the cooling rate at low temperatures has a greater effect on hard zone crack initiation than the rate at high temperatures.

It will be observed from Table XII that there was a greater amount of the hard zone cracking in the modification 2 test than in the modification 1 test. This could be explained by an increase in the cooling rate at lower temperatures, but in this instance there was also a difference in the degree of

Table XI.—Hardness and Cracking Data for Modifications of Reeve Tests. Steel Mn-Mo, Electrodes Type E. 217

Test Assembly	Plate Thickness (Inches)	Approximate Fillet Size (Inches)	Energy Input (Joules/in. $\times 10^{-3}$)	Average Peak Hardness in Hard Zone (V.P.N. 10 kg. load)	Average Weld Metal Hardness (V.P.N. 10 kg. load)	Hard Zone Cracking (Per cent. Leg Length)
Insulated Modified Full Reeve ..	1	3/16	18	473	297	31
		¼	29	470	273	19
		5/16	43	418	257	27
		13/32	63	381	238	12
Modification 1 Miniature Reeve ..	½	¼	29	403	269	23
		5/16	44	394	255	14
		7/16	75	323	213	Nil
Modification 2 Miniature Reeve ..	½	5/16	42	397	235	19

Table XII. Comparison of Results from Miniature Reeve Test and its Modifications. Steel Mn-Mo ½ in. Thick, Electrode 6 s.w.g., Class E.217

Test Assembly	Average Peak Hardness in Hard Zone (V.P.N. 10 kg. load)	Rate of Cooling (deg. C./sec.)			Cracking in Hard Zone (per cent.)
		At 300 deg. C.	At 200 deg. C.	At 200 deg. C.	
Miniature Reeve	393	4·4	0·95	0·42	Nil
Modification 1 miniature Reeve	394	6·5	1·7	0·57	14
Modification 2 miniature Reeve	397	9·0	2·9	0·67	19

external restraint and this extra restraint might have contributed to the increased cracking.

It would appear from the tests so far undertaken that a further investigation into the effect of low temperature ($<$400 deg. C.) cooling rate on hard zone cracking is necessary. It may be found that low temperature cooling rate is the controlling factor in crack initiation provided that the high temperature cooling rate is sufficiently fast to produce a hardness of 350-400 V.P.N. in the hard zone. Work is also necessary to determine the relative effects of external restraint and rate of cooling on hard zone crack initiation.

CONCLUSIONS

1. It has been shown that the modified full Reeve weldability test is more severe thermally than the miniature Reeve test. This difference in thermal severity is small at high temperatures but is large at lower temperatures ($<$400 deg. C.). This decrease in thermal severity gives some reduction in the amount of hard zone cracking when a Mn-Mo steel and class E.217 electrodes are used.

2. The thermal severity of the modified full Reeve test has been reduced by inserting insulating material between the bottom and base plates. The insulated test, when used with plates of given thickness, should give thermal severities equivalent to those occurring in a structural joint made on plates of the same thickness.

3. The mass of metal in the miniature Reeve test has been found to provide an inadequate heat sink and for this reason tests have been made with a base plate bolted to the standard test assembly. The thermal contact between this base plate and the bottom plate of the miniature Reeve test proved unsatisfactory due to bowing of the bottom plate as a result of welding.

4. The rate of cooling in the hard zone at temperatures below 400 deg. C. appears to have an effect on the incidence of hard zone cracking with the Mn-Mo steel when welded with class E.217 electrodes.

5. The Mn-Mo steel proved to be more weldable from the standpoint of hard zone cracking in the miniature Reeve test than the carbon-manganese steel when welded with class E.217 electrodes.

6. Class E.317 electrodes show less tendency to form hard zone cracks than class E.217 electrodes when welding the Mn-Mo steel in the miniature Reeve test.

ACKNOWLEDGMENTS

The authors are indebted to the British Welding Research Association for permission to publish this report.

Thanks are also due for the valuable discussions of the work by members of the FM.8 Committee of the British Welding Research Association and the High Tensile Weldable Structural Steel Investigation Steering Committee of the Ministry of Supply who jointly guided the investigation.

Particular thanks are due to Mr. J. G. Ball for the guidance which he gave to this investigation in its early stages.

REFERENCES

1. Hopkin, G. L. "A Suggested Cause and a General Theory for the Cracking of Alloy Steels on Welding." *Trans. Institute of Welding*, vol. 7, No. 2, pp. 76-78 (July, 1944).
2. Reeve, L. "A Summary of Reports of Investigations on Selected Types of High Tensile Steels," *Trans. Institute of Welding*, vol. 3, No. 4, pp. 177-202 (1940).
3. Dearden, J., and O'Neill, H. "A Guide to the Selection and Welding of Low Alloy Structural Steels," *Trans. Institute of Welding*, vol. 3, No. 4, pp. 203-214 (1940).
4. Barr, W. "Some Developments in Steels for Welded Structures," *Metallurgia*, pp. 79-84 (June, 1948).
5. Rosenthal, D. "Mathematical Theory of Heat Distribution during Welding and Cutting," *Welding Journal Research Supp.*, vol. 6, No. 2, pp. 220-234 (May, 1941).

R.77

THE WELDABILITY AND WELD STRENGTH OF SOME MAGNESIUM ALLOY SHEET MATERIALS

This report was first issued to members of the British Welding Research Association as a confidential document early in 1951.

By J. G. BALL,* B.Sc., A.I.M., and A. E. L. TATE,† A.I.M.

SYNOPSIS

The weldability and mechanical properties of certain magnesium base alloy sheet materials have been determined for oxy-acetylene and argonarc hand welding. After some preliminary investigations it was found necessary to devise a simple jig for testing weldability under the severe conditions of restraint which frequently develop in practice.

The alloys examined consisted of three binary magnesium alloys with aluminium contents up to 8 per cent., two ternary alloys with aluminium and zinc, four alloys with manganese and small additions of calcium, two alloys with cerium and manganese and two magnesium-zinc-zirconium alloys. The binary 7 per cent. aluminium alloy appeared to have the best combination of weldability and mechanical properties.

Small amounts of calcium and cerium were found to have a deleterious effect on the weldability of the magnesium-manganese alloys.

The magnesium-zinc-zirconium alloys Z3Z and ZW1 were found to be weldable by the argon arc process, although Z3Z was somewhat less weldable than ZW1.

INTRODUCTION

The object of the work to be described was the determination of the weldability and weld strength of magnesium alloys in the form of rolled sheet. During the war the use of magnesium alloy sheet for welded structures was mainly confined to the binary magnesium-manganese alloy AM503 which was easily rolled and welded, but had low strength. Investigations at the National Physical Laboratory[1] eliminated the difficulties of rolling high strength magnesium-aluminium alloys, and it was obvious that a strong alloy of this class, if weldable, might find many applications. Early work consisted of some simple exploratory weld tests on short panels cut from hot rolled sheet of various compositions in which aluminium was the principal alloying element. Later the tests, which were all carried out by Westland Aircraft Ltd., were extended to relatively long seam welds of 36 to 42 ins. in length on selected material both free and under partial restraint.

* Metallurgy Division, Atomic Energy Research Establishment, Harwell, formerly Senior Metallurgist, British Welding Research Association, London.

† Metallurgy Division, National Physical Laboratory, Teddington.

The relative weldability under considerable restraint of the various alloys had still to be determined and the subsequent work was carried out as a co-operative research by the British Welding Research Association and the National Physical Laboratory.

EARLY EXPLORATORY WORK

Short Seams

In this work the effect of aluminium additions with a varying manganese content was mainly investigated, and in addition some alloys containing aluminium and zinc of the AZ31 and AZM type were also examined. The composition of the materials is given in Table I. Tests were made on small panels cut from annealed hot rolled sheets. The seams were about 12 in. in length and were gas welded without restraint, using a filler rod cut from the parent metal. All the materials welded satisfactorily and the welder stated that he was unable to place them in any specific order of ease of welding. Tensile tests were made on the materials before and after welding and the results of these tests are also given in Table I. The welds were not trimmed before testing.

It is apparent that the presence of manganese and zinc in the alloys was of no consequence either on the weldability or weld strength. The results may be generalised by saying that within the limitations of the tests magnesium-aluminium alloys containing up to 9 per cent. of aluminium can be gas welded satisfactorily to give weld strengths superior to those obtained from the binary magnesium-manganese alloy AM503.

Long Seams

An alloy sheet material containing 7 per cent. of aluminium was examined for welding behaviour both free and under partial restraint. The materials were hot rolled sheets 42 and 36 ins. in length and 0·09 in. thick which were sawn longitudinally, giving panels about 6 in. in width. These panels were then welded using filler rods about $\frac{1}{8}$ in. wide cut from the sheet. A high-pressure torch was used and the seams made without tacking. Welding was commenced $1\frac{1}{2}$ in. from one edge working rightwards to the edge, the seam then being completed in a single run—except for slight pauses to flux the rod—restarting at the original starting point and carrying on to the remote edge. In the case of the weld under restraint a wooden backing block was used and the sheet cramped

Table I.—Early Exploratory Work—

Mechanical Tests on Magnesium Alloy Sheets

No.	Composition per cent.			Purpose of Test	Condition Tested	N.P.L. Tests		
	Al	Mn	Zn			Direction	Ultimate Stress Tons per sq.in.	Elongation per cent. on 2 in.
1	—	0·97	—	Effect of amount of manganese	Annealed 300 deg. C. —15 mins.	Long.	11·7	3·0
						Trans.	16·15	11·0
2	—	2·45	—			Long.	13·5	4·0
						Trans.	16·3	10·7
3	3·89	0·27	1·07	Effect of varying Aluminium with constant Mn and Zn	Annealed 350 deg. C. —30 mins.	Long.	18·8	10·7
						Trans.	19·4	14·2
4	6·13	0·29	0·97			Long.	18·9	8·7
						Trans.	19·4	15·0
5	8·62	0·22	1·00			Long.	19·4	—
						Trans.	20·8	23·0
6	0·57	1·30	—	Effect of Aluminium additions to AM.503 of constant Mn content	Annealed 300 deg. C. —30 mins.	Long.	13·4	4·0
						Trans.	16·8	14·5
7	0·96	1·16	—			Long.	14·3	5·2
						Trans.	17·0	16·0
8	1·49	0·96	—			Long.	15·7	8·7
						Trans.	16·9	18·0
9	1·99	1·03	—			Long.	15·8	9·0
						Trans.	17·1	18·0
10	2·45	1·02	—			Long.	15·9	8·0
						Trans.	17·5	18·0
11	3·01	1·17	—			Long.	15·8	8·7
						Trans.	17·0	23·0
12	3·80	0·58	—	Effect of Aluminium additions with more than 0·5 per cent. Mn present	Annealed 300 deg. C. —30 mins.	Long.	18·6	11·2
						Trans.	18·2	24·0
13	5·60	0·54	—			Long.	18·2	15·2
						Trans.	18·1	25·5
14	8·10	0·72	—			Long.	19·2	11·0
						Trans.	19·2	18·0
15	4·06	0·49	—	Effect of Aluminium additions with less than 0·5 per cent. Mn present	Annealed 350 deg. C. —30 mins.	Long.	17·0	15·2
						Trans.	17·3	21·7
16	5·78	0·49	—		Annealed 300 deg. C. —30 mins.	Long.	17·9	13·0
						Trans.	17·7	24·0
17	9·0	0·07	—	Effect of varying Mn on 9 per cent. Aluminium	Annealed 350 deg. C. —30 mins.	Long.	20·0	15·2
						Trans.	20·3	15·2
18	9·3	0·25	—			Long.	19·6	10·0
						Trans.	20·2	17·0
19	9·2	0·53	—			Long.	19·4	10·5
						Trans.	20·0	21·0
20	9·3	0·70	—			Long.	19·8	10·7
						Trans.	20·5	15·0

N.P.L. Tests. Mean of duplicate tests.

as shown in Fig. 1. A gap ¼ to 3/16 in. was found to be satisfactory. Visual examination showed the general quality of the weld to be very satisfactory with no signs of cracking.

Tensile tests were made on the welded sheets to examine the uniformity of the weld strength. Figs. 2 and 3 show the relative position of the test lengths cut from the sheets and their tensile properties. The tests show that while the parent material is reasonably uniform throughout its length, in the welded state the uniformity of the weld strength along the length is not so good. In the case of the sheet welded free, the proof stress measured in specimens which included the weld, varied between 6·6 to 9·8, the ultimate stress between 15·6 to 18·6 tons per sq.in., and the elongation between 3 to 10 per cent. In the sheet welded under restraint the respective ranges were 6·1 to 8·7 proof stress, 11·7 to 17·6 ultimate stress, and 1·5 to 7 per cent. elongation.

Table I.—Early Exploratory Work—*Continued*

Mechanical Tests on Magnesium Alloy Sheets Before and After Welding Short Seam Panels

No.	Westland Aircraft Tests							
	Unwelded Test Piece				Welded Test Piece			
	Direction	0·1 per cent. Proof Stress Tons per sq.in.	Ultimate Stress Tons per sq.in.	Elongation per cent. on 1 in.	Direction	0·1 per cent. Proof Stress Tons per sq.in.	Ultimate Stress Tons per sq.in.	Elongation per cent. on 1 in.
1	Long. Trans.	6·73 9·33	11·41 15·88	5·0 8·0	Long. Trans.	3·28 3·42	9·11 8·84	6·0 5·0
2								
3	Long. Trans.	11·41 13·23	17·78 17·99	11·0 10·0	Long. Trans.	8·92 7·89	16·5 15·12	9·0 6·0
4	Long. Trans.	11·7 11·94	17·12 18·68	9·0 13·0	Long. Trans.	6·8 9·11	11·86* 16·4	5·0 5·0
5	Long. Trans.	11·42 12·24	17·42 17·62	7·0 6·0	Long. Trans.	9·23 12·44	14·77 17·62	4·0 5·0
6	Long. Trans.	8·1 11·1	13·0 17·78	8·0 12·0	Long. Trans.	6·83 7·33	9·49 10·1	3·0 3·0
7	Long. Trans.	8·74 10·31	14·56 16·71	4·0 13·0	Long. Trans.	5·76 6·74	9·59 10·53	5·0 4·0
8	Long. Trans.	10·08 11·93	15·93 17·7	6·0 9·0	Long. Trans.	6·5 7·86	12·6 12·07	7·0 5·0
9	Long. Trans.	11·09 13·51	16·68 17·93	7·0 13·0	Long. Trans.	8·07 8·3	12·65 11·77	5·0 3·0
10	Long. Trans.	9·47 13·31	16·15 18·43	8·0 10·0	Long. Trans.	7·01 8·81	12·92 13·04	3·0 5·0
11	Long. Trans.	10·61 12·46	16·75 17·87	9·0 14·0	Long. Trans.	7·55 7·52	11·29 12·63	4·0 4·0
12	Long. Trans.	11·09 12·21	17·18 17·67	8·0 10·0	Long. Trans.	6·88 8·42	13·2 11·92	5·0 3·0
13	Long. Trans.	10·46 11·74	16·46 17·25	7·0 8·0	Long. Trans.	8·76 9·22	14·06 12·68	6·0 6·0
14	Long. Trans.	10·7 11·57	16·89 16·95	5·0 6·0	Long. Trans.	8·59 10·05	12·01 13·75	3·0 4·0
15	Long. Trans.	10·37 11·42	16·8 16·48	9·0 8·0	Long. Trans.	7·32 8·38	12·78 13·61	5·0 6·0
16	Long. Trans.	9·97 10·4	16·33 16·79	8·0 9·0	Long. Trans.	8·25 9·02	13·93 15·23	7·0 6·0
17	Long. Trans.	12·45 —	19·31 20·05	9·0 10·0	Long. Trans.	— —	15·02 20·28	3·0 9·0
18	Long. Trans.	11·93 13·05	19·28 19·8	10·0 12·0	Long. Trans.	— 12·63	16·76 19·28	3·0 10·0
19	Long. Trans.	11·87 13·32	17·57 18·63	8·0 10·0	Long. Trans.	9·17 4·10 } 7.10 8·02 8·78	13·5 5·95 } 11·44 14·88 8·59*	5·0 4·0
20	Long. Trans.	12·55 13·32	18·5 17·85	6·0 5·0	Long. Trans.	8·5 10·57	13·59 15·89	4·0 6·0

Westland Aircraft Tests. Mean of triplicate tests. * Fractures away from weld.

Conclusions from Exploratory Work

The main conclusion to be drawn from the early work was that small panels of magnesium-aluminium alloy sheet materials containing up to 9 per cent. of aluminium could be welded satisfactorily without restraint. The weld strength improves with aluminium content up to about 6 per cent. aluminium. Material containing 7 per cent. of aluminium—which was considered to be the practical limit of aluminium content—could also be welded in relatively long seams both free and under partial restraint. In the long seam weld examined the weld strength was good but varied somewhat along the length of the seam.

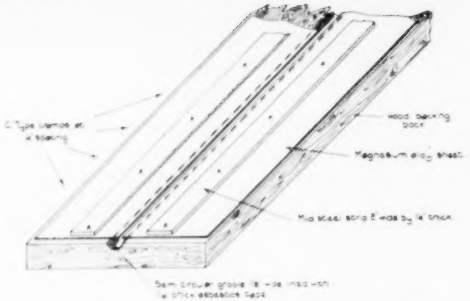
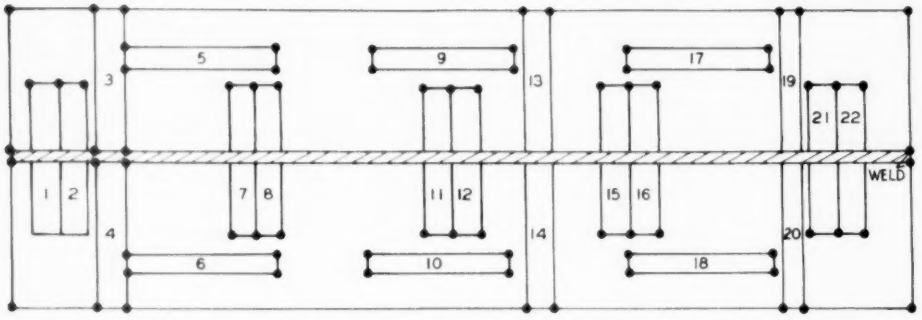


Fig. 1 *(right).* Sketch of backing block for cramping Mg alloy sheets for tests. (Restraint partial.)

Fig. 2 *(below).* Mechanical properties of Mg alloy (7 per cent. Al) welded sheet, welded in hot-rolled condition, without restraint. Seam length 42 in. (*Welding by Westland Aircraft Ltd.*)



Test Piece No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
0·1 per cent. proof stress	8·98	8·9	16·2	13·5	15·2	15·1	6·86	6·64	14·8	15·6	9·27	8·62	14·1	16·0	—	8·48	13·9	14·6	13·9	16·1	—	9·83
Ultimate stress	15·6	18·6	21·6	21·8	21·3	21·4	16·6	17·8	21·7	21·5	17·7	17·3	21·9	21·6	—	16·15	21·6	21·4	21·5	21·1	16·8	15·6
Elongation per cent. on 2 in.	3·0	10·0	12·0	9·0	11·0	10·0	5·0	7·0	12·0	10·0	6·5	7·0	12·0	11·0	—	4·0	10·0	11·0	15·0	9·0	4·5	3·5

Mean Values—

Unwelded Nos.	5	6	9	10	17	18			—	14·7	Proof stress	21·5	Ultimate stress	10·5	Elongation
Unwelded Nos.	3	4	13	14	19	20			—	15·0	tons per	21·6	tons per	11·0	per cent.
Welded Nos.	1	2	7	8	11	12	16	21	22	—	8·5	sq. in.	16·8	sq. in.	5·5	on 2 in.

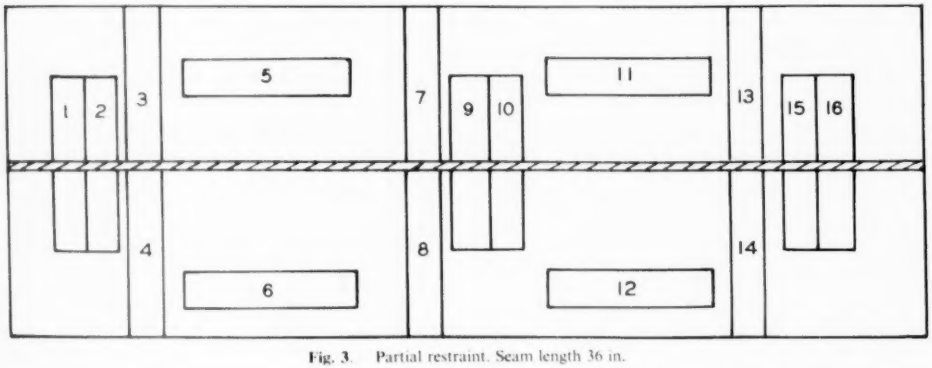


Fig. 3. Partial restraint. Seam length 36 in.

Test piece No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0·1 per cent. proof stress	8·69	8·42	16·0	16·5	15·2	15·0	16·1	16·7	6·15	9·45	15·4	15·2	16·5	16·5	6·96	8·63
Ultimate stress	16·7	17·1	22·0	21·4	21·3	20·8	22·1	22·5	11·7	16·8	21·4	17·9	22·0	22·2	12·7	17·6
Elongation per cent. on 2 in.	3·5	4·5	9·0	9·0	11·0	4·0	11·0	9·0	1·5	7·0	5·5	1·0	12·0	14·0	1·5	5·0

Mean Values—

Unwelded Nos.	5	6	11	12			—	15·15	Proof stress	20·4	Ultimate stress	5·5	Elongation
Unwelded Nos.	3	4	7	8	13	14	—	16·4	tons per	22·0	tons per	10·5	per cent.
Welded Nos.	1	2	9	10	15	16	—	8·05	sq. in.	15·4	sq. in.	4·0	on 2 in.

DETERMINATION OF WELDABILITY

Problems Involved in the Determination of Weldability

In this part of the investigation, observations have been made of the ease of welding, but greatest attention has been given to the tendency to crack. This can be measured accurately, but the ease of welding must be assessed by personal judgment.

To discriminate easily between sheet which was prone to crack and sheet which was readily weldable, a jig designed by Essex Aero Ltd., described by Winter[2] and illustrated in Fig. 4, was already in use by industry. This test required lengthy preparation and it was difficult to make the test weld. In addition this jig requires a greater width of sheet material than could be produced satisfactorily in the National Physical Laboratory mill for the work. The development of a test which was more easily manipulated and suitable for specimens which could be cut from sheet of maximum available width of 10½ in. was therefore considered. At the same time it was necessary for the test to incorporate the stress characteristics of the Essex Aero Ltd. jig which had been found to give results in close agreement with those obtained in practice. In consequence the Essex Aero jig was used in the present investigation for setting useful standards of severity and discrimination to be arrived at in devising a new weldability test.

Design of a Suitable Test

It seemed likely that the severity of test described by Winter was due to the fact that contractional stress would be set up in two directions—radial and circumferential. Practical experience, and a few tests,* showed that cracking was less severe when the sheets were restrained only transversely to the weld.

To overcome the welding difficulties inherent in any circular test, a test was required with a short straight weld, which retained the advantages of bi-axial restraint. This was done by gripping two sheets side by side in a strong rectangular steel frame.

In early experiments it was found that with smooth milled surfaces the sheets being welded could slip however tightly the jig was bolted together. Further experiments showed that this could be overcome by using gripping steel surfaces like those of a cross-cut file.

In the first jig, the central gap of the steel frame was too narrow. This resulted in a severe loss of heat by conduction to the steel jig and an abnormally large welding nozzle had to be used. It is interesting to note that this effect was more marked with the magnesium-manganese alloys than with the magnesium-aluminium alloys. The effect has been ascribed to the difference in thermal conductivity of the two types of materials. Average values of thermal conductivity from data quoted by Beck (Technology of Magnesium and its Alloys) are 0·33 C.G.S. units for the magnesium-manganese alloys and 0·17 C.G.S. units for the magnesium-aluminium alloys.

An attempt was made to reduce the heat loss to the jig by inserting insulating materials between the sheets and the steel plates, but it was concluded that it would be more satisfactory to increase the distance between the test weld and the edge of the central gap.

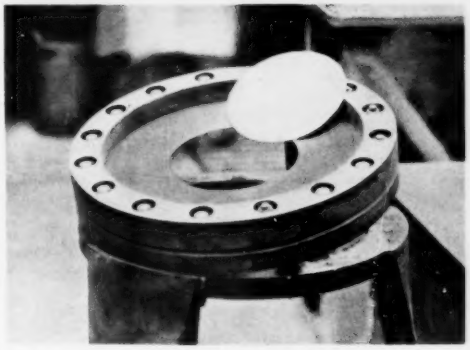


Fig. 4. Jig assembly for Essex Aero test.

Description of Test Assembly

The jig which has been used throughout these investigations incorporates the above principles and consists of two alloy steel plates 10 in. by 14 in., each with a central gap 4 in. wide and 10 in. long, having semicircular ends. The upper and lower plates are respectively ½ in. and 1 in. thick, the latter containing fixed studs for clamping together the plates. A dimensioned drawing of the jig is given in Fig. 5. The sheet to be welded is clamped firmly between the two plates. The inside surfaces of the plates of the jig are prepared as previously described to prevent slipping of the test sheets.

The test weld is made between two pieces of sheet each measuring 14 in. by 6 in., the gap between them being measured accurately by a feeler gauge during assembly. After the first test weld has been made, it can be cut out and the position of the sheets reversed so that a second test weld can be made on the same pair of sheets (this is described in greater detail in the section on experimental procedure). Fig. 6 shows the jig assembled and one of the test sheets being fitted over the studs.

Correlation of Results with Practice

As a result of practical experience during the war, it was found that the results from the Essex Aero circular patch test could be used directly to predict practical behaviour. If, therefore, correlation could be obtained between the results of a new test and results from the circular patch test, it could reasonably be assumed that the new test would also be giving results comparable with those obtained in practice. This criterion was adopted and the test results, given in Table II, indicate that the new test and the circular patch tests are about equally severe.

The advantage of the new test is that the preparation of the plates is more simple and it is easier to make the test weld.

It will be noted that two circular patch tests were made on material of the width supplied by the National Physical Laboratory. To make this possible the width of the sheet was increased by welding additional pieces to either side of the central panel. While this procedure made it possible to obtain a test result, it is obviously inconvenient for general use.

Materials

Ingots of alloys M7A, M8A, AZ31, AZM were supplied by Magnesium Elektron Ltd. and rolled at the National Physical Laboratory. Sheet materials of alloys M5A, Z3Z,

---

* Singer and Jennings[3] have described a jig which has been used successfully for aluminium-base alloys but which rigidly restrains the sheets in only one direction. It was thought that it would be interesting to compare the gas welding behaviour of the series of magnesium base alloys in the jig developed by Singer and in the B.W.R.A. jig. The alloys chosen for test were AZM (DTD 118), MKP, Downmetal MA and Z3Z. (See Table III.)

With the exception of the magnesium-zinc-zirconium (Z3Z) alloys no cracks were formed. In the magnesium-zinc-zirconium alloy there was partial cracking for about 40 per cent. of the test weld length. Comparison with the results on these alloys obtained in the B.W.R.A. jig indicates that the Singer jig is less severe. It should be noted that in the Singer jig there is no possibility of the sheet slipping which indicates therefore, that the increased severity of the B.W.R.A. jig is due to the development of a bi-axial system of stresses.

Table II.—Correlation of Severity in the B.W.R.A. and Essex Aero Weldability Tests

Alloy Type	Designation or Code Marking	B.W.R.A. Jig	Essex Aero Jig
Magnesium-manganese	AM503	No cracking	No cracking†
Magnesium-aluminium-zinc	AZM	Average 3 per cent. junction cracking	9 per cent. junction cracking*
Magnesium-aluminium	M8A	4 per cent. junction cracking	3 per cent. junction cracking*
Magnesium-manganese-calcium	Dowmetal MA	35 per cent. junction cracking	16 per cent. junction cracking†
Magnesium-manganese-calcium	MKS	100 per cent. junction cracking§	Extensive but incomplete cracking‡

* Tests made in B.W.R.A. laboratories.
† Tests made by Essex Aero Ltd.
‡ Private communication from J. Pendleton.
§ This value was obtained even under the less severe conditions of preliminary tests.

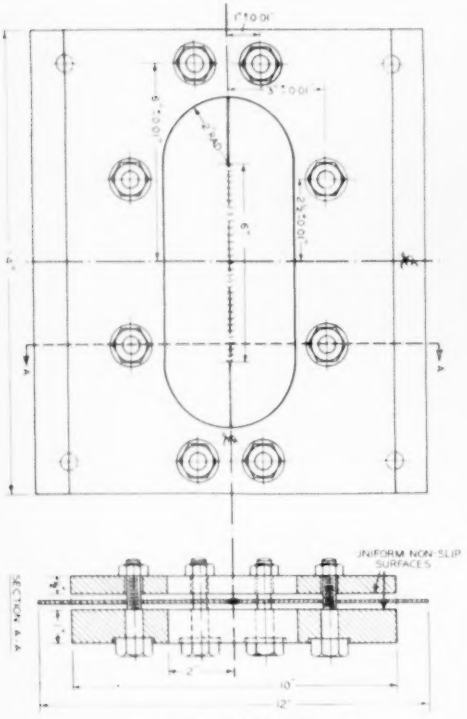


Fig. 5. Drawing of B.W.R.A. jig.

Fig. 6. B.W.R.A. weldability test, partly assembled.

ZW1 and Dow MA were supplied by industry. The remaining materials were cast and rolled at the National Physical Laboratory.

The alloys tested were supplied in either 14 s.w.g. or 16 s.w.g. sheet. Table III gives the composition, code markings and thicknesses of sheets which have been tested. Except for some of the tests on the zirconium alloy sheets the filler rods were of the same composition as the test sheets and were cut from the sheets on a milling machine to ensure that they were of uniform rectangular section.

Experimental Procedure

Preparation and Assembly of Plates.—Two rectangular pieces 14 in. by 6 in. are cut from the alloy to be tested and drilled to fit over the studs of the test jig. These drilled holes (½ in. diameter) are made slightly larger than the studs (7/16 in. diameter) to allow for adjustment of the gap width.

Fig. 7 shows that with the sheet sizes given above, two welding tests can be made. The holes in the sheets are so arranged that after making a test between the edges CD and EF the weld can be cut out and the sheets reversed for a second test to be made between the edges AB and GH.

In most of the gas welding tests a gap width of 0·030 in. was used and this was set by a feeler gauge. In some instances smaller gaps were used or the sheets were close-butted, details being given in Table IV.

For argonarc welding most of the tests were made with the sheets close-butted as in normal practice.

Oxy-Acetylene Welding Technique.—In accordance with normal practice for 14 or 16 s.w.g. sheet a B.O.C. No. 3 nozzle was used, a pressure of 2 lbs. per sq.in. being used for both the oxygen and the acetylene. Retaining this standard procedure for all alloys, there was still some variation in the speed of welding, but this was rarely outside the range of normal practice. B.O.C. Magnotectic flux, made up as a water paste, was applied to the filler wire and to the underside of the sheets to be welded.

Argonarc Welding Technique.—Arc welding equipment, with apparatus for superimposing a high frequency current, was used, the diameter of the tungsten electrode being ⅛ in. for all the tests. The flow of argon was adjusted to 3 litres per minute. Current and voltage settings for the individual tests are reported in Table IV and varied between 60 to 120 volts, 38 to 85 amps.

Examination of Test Welds.—The tests welds were examined for cracks visually and under a binocular microscope up to ×20 magnifications. Three types of cracking were observed, and in practice one or more of these types

Table III.—Composition of Magnesium Alloy Sheets Investigated in Jig Tests

Alloy Type	Designation or Code Marking	Al per cent.	Mn per cent.	Zn per cent.	Fe per cent.	Ca per cent.	Ce per cent.	Zr per cent.
Magnesium-aluminium and magnesium-aluminium-zinc alloys (14G. sheet)	AZ31	3·4	0·26	0·94	0·004	—	—	—
	M5A†	5·0†	—	—	—	—	—	—
	AZM	5·8	0·21	0·95	0·003	—	—	—
	M7A	6·9	0·20	—	0·004	—	—	—
	M8A	7·9	0·20	—	0·005	—	—	—
Magnesium-manganese alloys with calcium (16G. sheet)	AM503	—	2·43	—	—	0·01	—	—
	MPY2* (Dowmetal MA)	—	1·5†	—	—	0·09‡	—	—
	MKP*	—	1·5†	—	—	0·14‡	—	—
	MKS*	—	1·5†	—	—	0·19‡	—	—
Magnesium-zinc-zirconium alloys (14G. sheet)	Z3Z§	—	—	3·0†	—	—	—	0·6
	ZW1	—	—	1·25†	—	—	—	0·5†
Magnesium-manganese-cerium alloys 14G. sheet)	AM537	—	1·53	—	—	—	0·52	—
	Mader and Laves alloy	1·20	1·05	—	—	—	0·59	—

Filler rods were cut from parent metal. To ensure a uniform, rectangular section the filler rods were cut from the main sheet on a milling machine.
* Commercially made sheets.
† Nominal contents.
‡ Calcium determinations kindly made by the B.N.F.M.R.A.
§ The code for alloys of this composition has been changed by the manufacturers from Z3Z to ZW3.

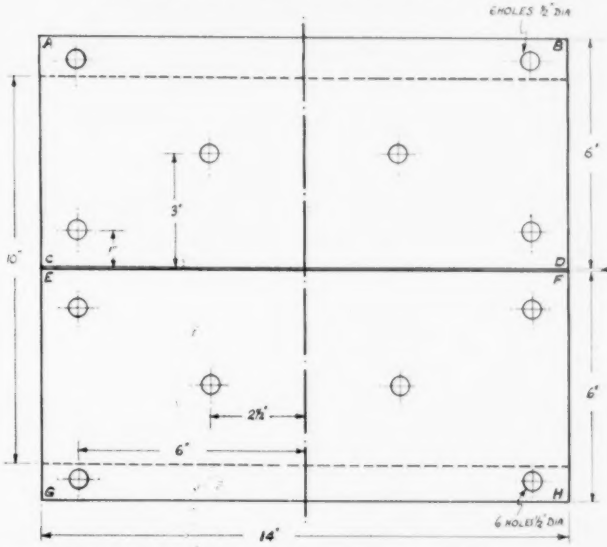


Fig. 7 (*left*). Drawing of plates for B.W.R.A. jig.

could occur in a single test weld:

Junction cracks—formed in the fusion zone between the weld bead and the parent plate.

Weld cracks—formed in the weld metal in the direction of welding and usually in the centre of the weld bead.

Crater cracks—formed at the end of the weld and consisting either of a single crack or of several cracks spreading radially from the centre of the end pool.

Weld cracks and crater cracks can usually be seen with the naked eye, but junction cracks can sometimes only be detected under the microscope. Where there was any doubt about junction cracks, sections were prepared and examined microscopically.

For each test weld a section parallel to the surface of the sheet was etched as it was known from the work of Pendleton[4] that excessive grain growth in the parent metal could best be detected in this way.

Results

The experimental results are described under the headings of the alloy types given in Table III, while the complete results, together with the appropriate test conditions, are set out in Table IV.

The more localised heating obtained with argonarc welding gives greater penetration and permits close-butting of the sheets or the use of a small gap. Most of the argonarc welding tests have therefore been made with the sheets close-butted. The reduced cracking obtained with argonarc welding is partly due to close-butting since in tests 38, 39 and 40 (Table IV) junction cracking increases with an increase in gap width. Further, test Nos. 28 and 29 and test Nos. 36 and 37 in Table IV, show that with gas welding the same effect is obtained. Unfortunately it is difficult to maintain good penetration with gas welding if the gap width is small.

Table IV.—Weldability Tests on Magnesium Alloys

Test Ref	Designation or Code Marking	Nominal Composition	Plate Thickness S.W.G.	Welding Process	Special Test Conditions	Gap Width ($\times 10^{-3}$ in.)	Welding Time (secs.)	Junction Cracking (% of Weld Length)	Weld Cracking and Crater Cracking
1	AZ31	3% Al. 1% Zn	14	Oxy-acetylene		30	39	0	Crater cracking
2	"	"	14	"		30	—	0	" "
3	M5A (normal purity)	5% Al.	14	"		30	—	0	None
4	"	"	14	"		30	—	0	None*
5	AZM	6% Al. 1% Zn	14	"		30	35	6	Crater cracking
6	"	"	14	"		30	30	0	" "
7	"	"	14	"	Crater feeding	30	—	0	None
8	"	"	14	"	" "	30	—	0	"
9	"	"	14	"	Welding over 4 tacks	30	—	0	"
10	M7A	7% Al.	14	"		30	30	0	Some weld cracking and crater cracking
11	"	"	14	"	Crater feeding	30	—	0	None
12	"	"	14	"	Welding over 4 tacks	30	—	0	"
13	M8A	8% Al.	14	"		30	37	4	Slight weld cracking
14	"	"	14	"		30	—	0	Very slight crater cracking
15	AZ31	3% Al. 1% Zn	14	Argonarc 120v/50a		0	—	0	None
16	"	"	14	"		0	—	0	"
17	M5A (normal purity)	5% Al.	14	"		0	—	0	"
18	M5A (normal purity)	5% Al.	14	"		0	—	0	None
19	M5A (high purity)	"	14	"		0	—	0	"
20	"	"	14	"		0	—	0	"
21	AZM	6% Al. 1% Zn	14	"		0	—	0	"
22	"	"	14	"		0	—	0	"
23	M7A	7% Al.	14	"		0	—	0	"
24	"	"	14	"		0	—	0	"
25	M8A	8% Al.	14	"		0	—	0	"
26	"	"	14	"		0	—	0	"
27	AM503	2% Mn trace Ca.	14	Oxy-acetylene		30	41	0	"
28	Dowmetal MA	2% Mn 0·09% Ca†	16	"		30	48	35	"
29	"	"	16	"		0	33	0	"
30	Dowmetal MKP*	2% Mn 0·14% Ca†	16	"		30	65	100	Slight weld cracking
31	AM503	2% Mn trace Ca.	14	Argonarc 120v/50a		0	—	0	Crater cracking
32	"	"	14	"		0	—	0	Crater cracking
33	Dowmetal MKS	2% Mn 0·19% Ca†	16	"		0	32	100	Some weld cracking
34	ZSZ	3% Zn 0·5% Zr	14	Oxy-acetylene		30	58	100	Severe weld cracking
35	"	"	14	"		30	38	100	" " "
36	"	"	14	"		30	83	100	" " "
37	"	"	14	"		0	40	8	Some weld cracking
38	ZSZ	3% Zn 0·5% Zr	14	Argonarc 120v/50a		30	60	100	Severe weld cracking
39	"	"	14	Argonarc 60v/38a		10	37	8	Some weld cracking
40	"	"	14	Argonarc 60v/35a		0	49	0	Crater cracking only
41	ZW1	1·25% Zn 0·5% Zr	14	Argonarc 100v/85a	Welded with ZZ2C filler rod	20	30	0	Slight crater cracking
42	"	"	14	Argonarc 100v/78a		20	89	0	Slight crater cracking
43	AM537	1·5% Mn 0·5% Ce	14	Oxy-acetylene		30	71	100	Slight weld cracking
44	"	"	14	"		30	—	38	Crater cracking
45	To composition of Mader and Laves	1·5% Mn 0·5% Ce	14	"		30	40	0	None
46	" "	" "	14	"		30	—	0	Slight crater cracking
47	AM537	1·5% Mn 0·5% Ce	14	Argonarc 120v/50a		0	—	0	Slight weld cracking
48	To composition of Mader and Laves	1·5% Mn 0·5% Ce with 1% Al.	14	"		0	—	0	None
49	" "	" " "	14	"		0	—	0	None

* This value was obtained using one of the early jigs and was confirmed in two other similar tests. Insufficient sheet was available for testing the alloy in the jig finally adopted, though it is almost certain that complete cracking would again have been produced as the final jig was more severe than the early assemblies.

† Actual content.

No cases of excessive grain growth in the parent metal were observed. The grain size of the weld metal is discussed in the appropriate sections on the various types of alloy.

Magnesium-Aluminium and Magnesium-Aluminium-Zinc Alloys of the DTD 120 Type

Oxy-Acetylene Welding.—In this group five alloys of various aluminium contents were tested. In most of these tests there was crater cracking which seems to be characteristic of the alloys containing aluminium, apparently increasing with increasing aluminium content or in the presence of zinc. There was a tendency for the crater cracking to extend into the weld with the alloys of higher aluminium content. A typical crater crack is shown in Fig. 8.

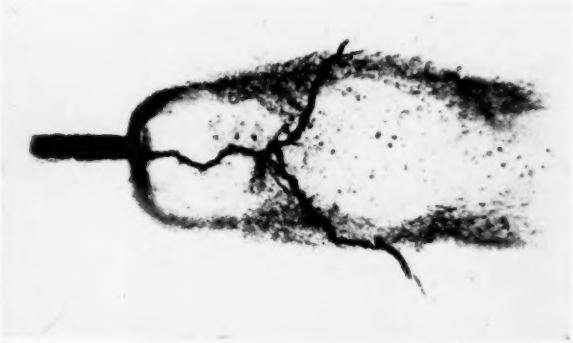


Fig. 8. Crater cracking in AZM alloy. (×4)

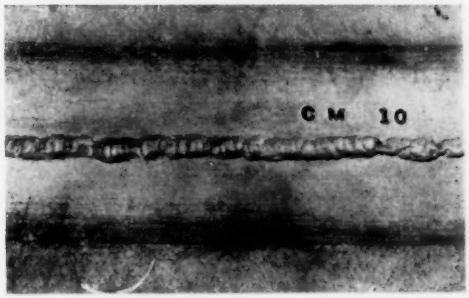


Fig. 9. Junction cracking in Mg-Mn alloy. (0·14 per cent. Ca). (×½)

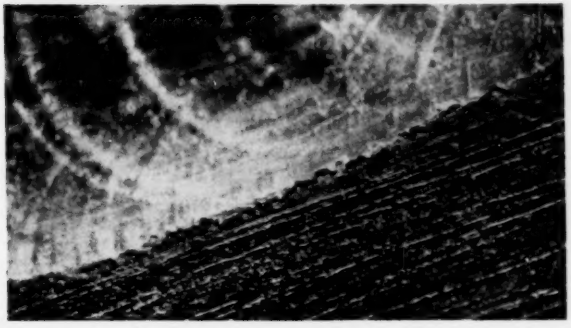


Fig. 10. Junction cracking in Mg-Mn alloy (0·09 per cent. Ca). (×12)

It was found that crater cracking in the AZM and M7A alloys could be eliminated either by feeding the end pool or by running into a tack at the end of a test weld. The results of this series of experiments are given in Table IV under Test Nos. 7, 8, 9, 11 and 12. In practice feeding the end pool can be achieved by withdrawing the filler rod and flame slowly to avoid a shallow crater.

Some work by Pendleton[4] had shown that in some cases welding over tack welds caused excessive grain growth and there was a possibility of cracking in the region of the tack. No such effect was found in the present work on two of the alloys, where four equally spaced tacks were made outside the jig before testing. (See Tests 9 and 12, Table IV.)

Junction cracking was found in the alloys containing 8 per cent. aluminium and 6 per cent. aluminium-1 per cent. zinc, but in the latter alloy it occurred in only one of the two tests. As there was no junction cracking in the alloys containing 5 and 7 per cent. aluminium, it appears that the addition of zinc to these alloys increases the tendency to crack. Figs. 11 and 12 illustrate the microstructures of the plate metal and weld metal respectively in the magnesium-6 per cent. aluminium-1 per cent. zinc alloy (AZM), and Figs. 13 and 14 show the corresponding structures for the magnesium-7 per cent. aluminium alloy (M7A). It will be seen that the grain size of the parent metal is very small, and while it was difficult to etch the grain structure of the weld metal, the grain size is evidently greater than that of the sheet. The disparity in grain size between weld metal and sheet is generally less with the magnesium-aluminium alloys than with the magnesium-manganese alloys.

Argonarc Welding.—No junction or crater cracking occurs when any of the alloys of this group is argonarc welded in the test jig. (Tests Nos. 15 to 26 inclusive, Table IV.)

Magnesium-Manganese Alloys of the DTD 118 Type

In general, the magnesium-manganese alloys are the most easily welded by gas and argonarc and the least prone to either crater or junction cracking. This general finding is in agreement both with experience in practice and with results from the Essex Aero circular patch test.

With the magnesium-manganese type alloys, the weld bead usually meets the plate at a sharp angle (see Fig. 9), whereas with the magnesium-aluminium alloys the weld fuses to the plate metal with a smooth contour. This difference is probably due to the marked difference in freezing range, which is extended in the aluminium alloys and very short in the magnesium-manganese alloys.

Magnesium-Manganese Alloys Containing Calcium

Oxy-Acetylene Welding.—Practical experience of tests with the Essex Aero jig has shown that if calcium is present in sufficient quantities, it will cause cracking during welding with the magnesium-manganese alloys. In the present investigations most of the tests have been carried out on alloys containing from 0·09 per cent. calcium to 0·19 per cent. calcium, and it has been found that cracking occurs with gas welding in all of these alloys. At the higher calcium contents the cracks are easily observed, and Fig. 9 shows severe junction cracking in the alloy containing 0·14 per cent. calcium (MKP alloy). The test from which this sample was taken was made with one of the early experimental jigs. Unfortunately there was not enough sheet material remaining to make a further test in the final jig, but there is no reason to suppose that the behaviour would be different. With 0·09 per cent. calcium content, cracking is less easily observed and with a casual inspection the weld might be considered sound. However, the cracks can be readily observed at low magnification, and Fig. 10 shows a typical crack obtained with the alloy containing 0·09 per cent. calcium (Downmetal MA).

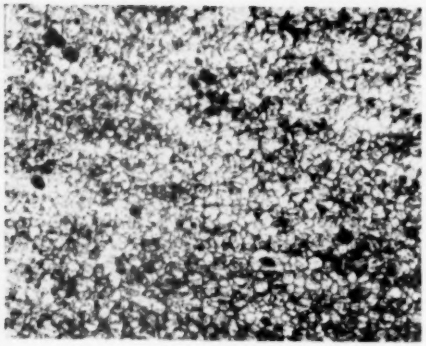


Fig. 11. Plate structure in AZM alloy. Etched in 1 per cent. oxalic acid. (×100)

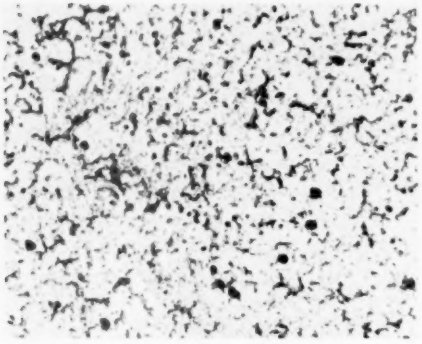


Fig. 12. Weld structure in AZM alloy. Etched in 1 per cent. oxalic acid. (×100)

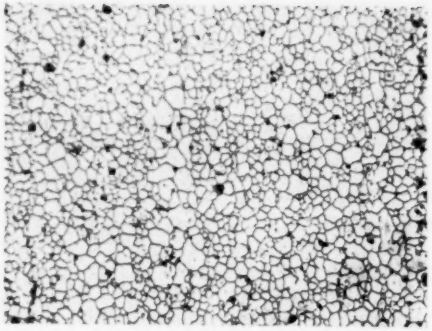


Fig. 13. Plate structure in M7A. Etched in 1 per cent. oxalic acid. (×100)

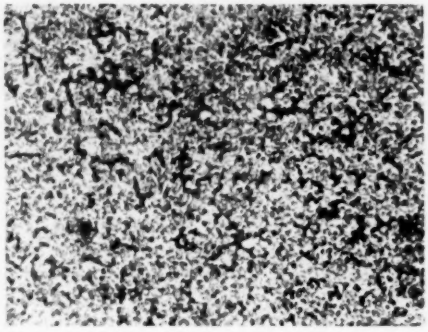


Fig. 14. Weld structure in M7A. Etched in 1 per cent. oxalic acid. (×100)

This crack was found to penetrate about one-quarter of the thickness of the sheet. One of the alloys tested contained a trace of calcium (estimated to be less than 0·01 per cent.) and no cracking was observed.

The foregoing tests were made with a gap width of 0·030 in. A further test was made on the alloy containing 0·09 per cent. calcium in which the plates were close butted. It was found that while junction cracking was entirely eliminated it was not possible to obtain normal penetration. On the other hand, with a normal gap (0·030 in.) considerable cracking was observed (35 per cent. of the weld length).

The microstructure of the parent metal and the weld metal for the magnesium-manganese alloy (AM503) containing a trace of calcium (0·01 per cent) are shown in Figs. 15 and 16 respectively. It will be noted from Table III that this particular alloy contains more manganese (2·43 per cent.) than the other alloys of this group. Figs. 17 and 18 show the parent metal and weld metal respectively of the alloy containing 0·14 per cent. calcium (MKP alloy).

Argonarc Welding.—Argonarc welding tests on the magnesium-manganese alloy (AM503) again showed no junction cracking, though in this case slight crater cracking was observed. A test was made on the alloy containing 0·19 per cent. calcium with the plates close-butted, and while some cracking was found in the weld metal the junction was crack-free.

Magnesium-Zinc-Zirconium Alloys (Z3Z and ZW1)

Oxy-Acetylene Welding.—Although the manufacturers do not recommend oxy-acetylene welding of these alloys, a number of tests have been made with the alloy Z3Z containing 3 per cent. zinc and 0·6 per cent. zirconium. Using oxy-acetylene welding, the alloy is liable to severe cracking when the sheets are restrained by welding in the jig. Tests made in the jig have shown complete separation of the plates by cracking, which occurs both in the weld and along the junction. With no gap between the plates, cracking was much less, but the penetration was poor, and severe buckling occurred. A gap of about 0·030 in. facilitates penetration.

Figs. 19 and 20 show the microstructures of the plate metal and the weld metal respectively of the magnesium-zinc-zirconium alloy. With this alloy the grain size of the weld metal is unusually small. Fig. 19 shows the plate structure to be heavily worked although the alloy was supplied in the hot-rolled condition.

In view of the heavily worked structure of the plate metal, tests have been made on the material after annealing for four hours at 310 deg. C. This treatment did not reduce the tendency to crack.

Argonarc Welding.—With argonarc welding and using a gap of 0·030 in. between the plates, complete cracking occurred along the junction, together with some weld cracking in the Z3Z alloy. It was found that the cracking diminished as the gap between the plates was reduced. As may be seen from test 39, Table IV, with a gap of 0·010 in. junction cracking was reduced to 8 per cent., though weld cracking was still severe. With no gap between the plates, and using filler rods of the same composition as the parent

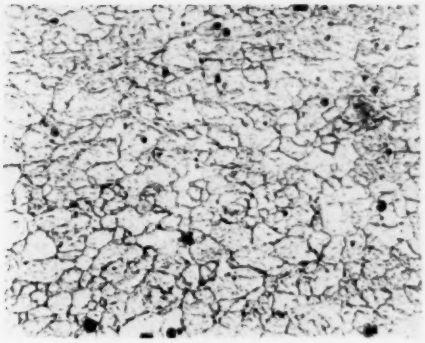


Fig. 15. Plate structure in Mg-Mn alloy (0·01 per cent. Ca). Etched in 1 per cent. oxalic acid. (× 100)

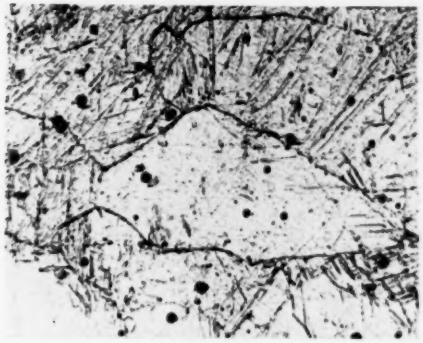


Fig. 16. Weld structure in Mg-Mn alloy (0·01 per cent. Ca). Etched in 1 per cent. oxalic acid. (× 100)

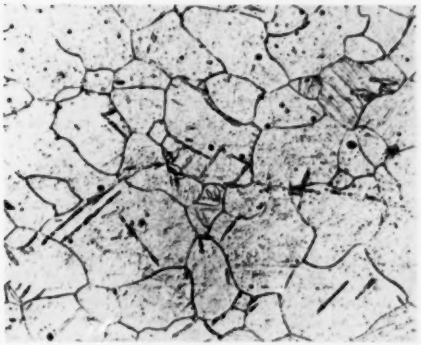


Fig. 17. Plate structure in Mg-Mn alloy (0·14 per cent. Ca). Etched in 1 per cent. oxalic acid. (× 100)

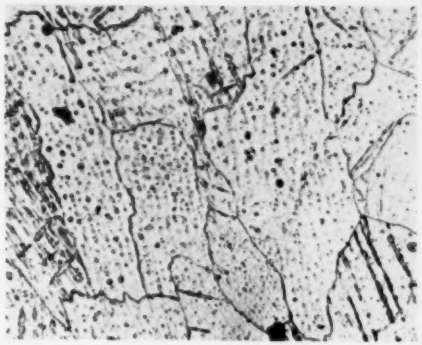


Fig. 18. Weld structure in Mg-Mn alloy (0·14 per cent. Ca). Etched in 1 per cent. oxalic acid. (× 100)

Fig. 19. Plate structure in Z3Z alloy (0·6 per cent. Zr). Etched in 5 per cent. nital. (× 100)

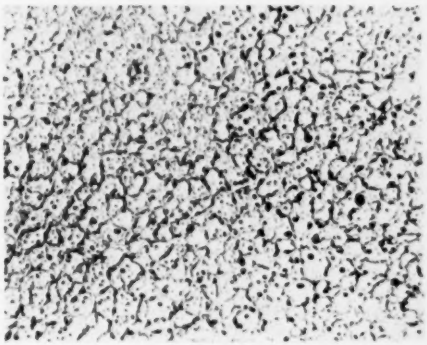


Fig. 20. Weld structure in Z3Z alloy (0·6 per cent. Zr). Etched in 1 per cent. oxalic acid. (× 100)

metal, junction cracking was eliminated, and weld cracking was limited to the crater at the end of the weld. No test was carried out on the Z3Z alloy using the special filler rod described below.

The ZW1 alloy has been welded without junction cracking with a gap of 0·020 in. between the plates using the argonarc process and a special filler rod (Z2Z2C filler containing 2 per cent. zinc, 2½ per cent. cadmium and 0·5 zirconium). Slight crater cracking was obtained, but it should be possible to overcome this defect by a suitable weld-terminating technique similar to that described previously. Figs. 21 and 22 show the structures of the plate metal and weld metal respectively. The plate metal has a typically worked structure. As with the Z3Z alloy, the weld metal has an unusually small grain size.

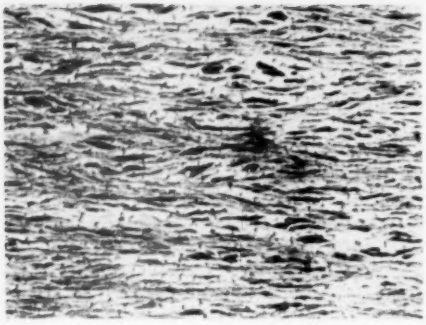


Fig. 21. Plate structure in ZW1 alloy. Etched in 2 per cent. nital. (× 100)

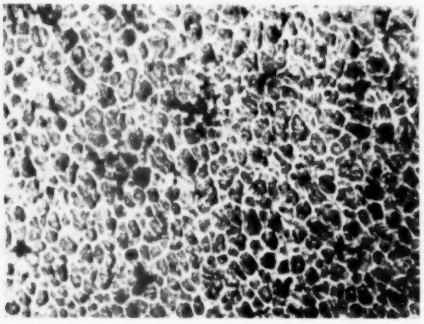


Fig. 22. Weld structure in ZW1 alloy. Etched in 2 per cent. nital. (× 100)

Magnesium-Manganese Alloys containing Cerium and Aluminium

Oxy-Acetylene Welding.—It is well known that the addition of cerium (in the form of Mischmetall) to a magnesium-manganese alloy improves its mechanical properties and in particular the creep strength and elongation. Alloys containing cerium were available in Germany under the designation Elektron AM537. Mader and Laves[5] found that the presence of cerium in these alloys induces cracking on welding under restraint, but claimed that the addition of approximately 1 per cent. aluminium improved the weldability of alloys containing from 0·2 to 0·3 per cent. cerium. The metallographic work of Mader and Laves on these alloys indicated the reasons for the improvement in weldability. In the straight cerium alloys the cerium occurs as a brittle compound $CeMg_9$ which, after overheating, is precipitated at the grain boundaries where fracture is initiated by the shrinkage stresses associated with welding. Additions of aluminium tend to decrease the amount of the compound $CeMg_9$ in the structure, $CeAl_2$ being formed preferentially as fine particles distributed throughout the structure. When there is sufficient aluminium present to prevent the formation of harmful amounts of $CeMg_9$, cracking during welding is eliminated. The amount of aluminium required to do this is much greater than that theoretically necessary for forming $CeAl_2$ because, according to Mader and Laves, a magnesium-aluminium solid solution can exist in equilibrium with the $CeAl_2$.

These claims have been confirmed by the present series of gas welding tests. It was found that an alloy of the Elektron AM537 type containing 0·6 per cent. cerium (added as Mischmetall) cracked completely along the weld junction (together with slight weld cracking in the crater) in the B.W.R.A. test. The addition of 1 per cent. aluminium to this alloy was found to eliminate cracking, thus substantiating the claim for the beneficial effect of aluminium on the welding of magnesium-cerium-manganese alloys made by Mader and Laves. Figs. 23 and 24 show the microstructure of the sheet and weld metal respectively for the Elektron AM537 type alloy, and Figs. 25 and 26 are the corresponding microstructures for the alloy containing aluminium. In both alloys the grain size of the weld metal is much greater than that of the sheet. It will be seen that the addition of aluminium to the magnesium-manganese alloys has little effect on the grain size of the weld metal. The grain boundaries of the weld metal in the aluminium-containing alloys are much more irregular than those in the Elektron AM537 type alloy. In addition these grain boundaries are thinner and these two observations are consistent with suggestions put forward by Mader and Laves to explain the improvement due to aluminium.

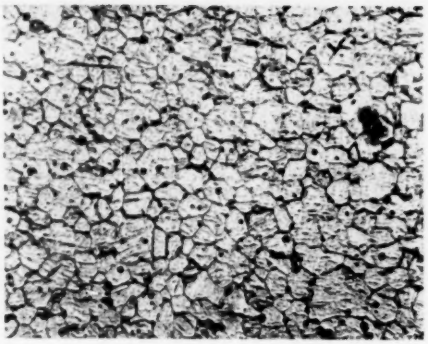


Fig. 23. Plate structure in AM537. Etched in 1 per cent. oxalic acid. (× 100)

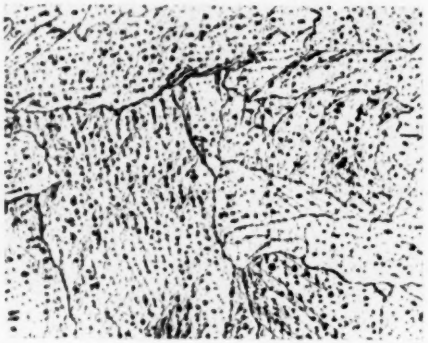


Fig. 24. Weld structure in AM537. Etched in 1 per cent. oxalic acid. (× 100)

Argonarc Welding.—With argonarc welding, cerium is not so deleterious as with gas welding, although there was slight weld cracking. As before, no cracking of any kind was found in the cerium alloy containing added aluminium.

DETERMINATION OF MECHANICAL PROPERTIES

Tensile tests were made on the sheet materials in the hot-rolled condition and on specimens after welding. Owing to

Table V.—Tensile Properties of Magnesium Alloy Sheet Materials before and after Welding

No.	Alloy	Direction of Test	Before Welding: 0·1% Proof Stress,‡ Tons per sq. in.	Before Welding: Ultimate Stress, Tons per sq. in.	Before Welding: Elongation % on 2 in.	(N.B.—Not Jig Tests but Welded in Short Panel) After Welding: Gas Welded: Ultimate Stress, Tons per sq. in.	Gas Welded: Elongation % on 2 in.	Argonarc Welded: Ultimate Stress, Tons per sq. in.	Argonarc Welded: Elongation % on 2 in.
			A / B						
1	Mg-Mn (2·4 Mn)	Long.	4·6 / 5·2	11·3	5·0	5·3*	1·5	6·6	2·0
						9·8	1·5	5·6	2·0
	AM503		5·2 / 5·4	11·8	5·0	4·4	1·5	8·7*	2·0
		Trans.	6·9 / 7·4	14·3	10·5	—	—	—	—
			7·0 / 7·4	15·1	7·5	—	—	—	—
2	Mg-Mn-Ca† (1·5Mn, 0·09 Ca) ..		— / —	—	—	6·6	1·0	9·6	2·5
	MPY2 (Dowmetal MA)					7·6	2·0	10·0	2·5
						7·0	1·5	—	—
3	Mg-Mn-Ce-Al (Mader and Laves) (1·05 Mn, 0·5 Ce, 1·2 Al)	Long.	7·1 / 8·9	14·2	9·6	11·3	1·5	6·8	1·5
						6·8	1·0	7·2	1·5
	Mader and Laves alloy		7·6 / 8·2	14·3	8·0	12·5	2·0	9·2	1·5
		Trans.	9·0 / 9·3	16·3	14·5	—	—	—	—
			8·8 / 9·9	16·3	13·0				
4	Mg-Mn-Ce (1·53 Mn, 0·5 Ce) ..	Long.	8·9 / 9·4	14·5	10·0	9·9*	3·0	10·7*	3·0
						8·0*	2·0	9·2	3·0
	AM537		8·5 / 8·8	14·7	9·5	6·7*	2·0	10·4*	3·0
		Trans.	10·1 / 11·4	15·0	19·5	—	—	—	—
			11·2 / 12·1	16·4	15·0				
5	Mg-Al† (5 Al)	Long.	—	—	—	16·1	10·5	8·9*	2·5
						15·1*	6·5	14·4*	6·0
	M5A					12·5*	4·5	14·0*	6·5
		Trans.	—	—	—	—	—	—	—
6	Mg-Al (7 Al)	Long.	— / 12·7	20·2	14·0	16·6	4·0	16·7	2·0
						16·2*	4·0	17·5	2·5
	M7A		13·0 / 14·6	21·0	19·5	18·8	7·0	16·3*	3·0
		Trans.	— / 14·4	21·4	18·5	—	—	—	—
			14·2 / 14·7	21·2	19·0				
7	Mg-Al (8 Al)	Long.	15·6 / 16·4	23·5	13·0	19·6	7·0	17·0	3·5
						19·3	6·0	17·8	2·5
	M8A		15·6 / 16·4	23·4	12·5	17·4*	4·5	16·6	2·5
		Trans.	15·5 / 16·9	23·4	15·0	—	—	—	—
			16·2 / 16·3	23·6	17·0				
8	Mg-Al-Zn (3·5 Al, 1 Zn)	Long.	12·9 / 13·6	18·6	12·0	16·9	7·0	15·3	4·0
						16·5	6·0	16·5	4·5
	AZ31		12·7 / 13·6	18·6	10·5	16·8	7·5	9·0*	2·5
		Trans.	14·3 / 15·3	19·0	19·0	—	—	—	—
			14·9 / 15·2	19·0	20·5				
9	Mg-Al-Zn (6 Al, 1 Zn)	Long.	16·0 / 16·9	22·3	17·5	19·3	9·0	10·1*	1·5
						17·2*	5·0	11·7*	1·5
	AZM		16·2 / 17·1	22·3	11·5	15·0	4·5	12·2*	1·5
		Trans.	16·9 / 17·6	22·4	15·0	—	—	—	—
			16·2 / 17·5	22·5	17·5				
10	Mg-Zn-Zr† (3 Zn, 0·6 Zr) ..	Long.	11·4 / 11·7	17·4	6·5	13·6	6·0	10·6	1·5
						12·8*	3·5	14·5	2·0
	Z3Z		11·4 / 11·7	17·6	8·5	11·5	2·0	11·3	1·5
		Trans.	12·3 / 13·1	18·8	22·5	—	—	—	—
			12·7 / 13·2	18·9	22·0				
11	Mg-Zn-Zr† (1·25 Zn, 0·5 Zr) ..	Long.	10·6 / 11·9	17·4	2·5	—	—	13·9	5·5
								12·6	5·0
	ZW1		9·8 / —	17·0	3·0	—	—	13·8	6·0
		Trans.	12·0 / 11·9	20·1	22·0	—	—	12·6	2·5
								12·7	1·5
			12·0 / 12·5	19·7	17·5	—	—	9·9	2·0

* Broke in weld metal. † Sheet material supplied by industry.

‡ *Method A* entails drawing a line parallel to the entire straight portion of the curve and assumes that the unloading line from the proof load is parallel thereto.

Method B entails obtaining an unloading line and drawing a line parallel to it from 0·1 per cent. permanent extension at zero load.

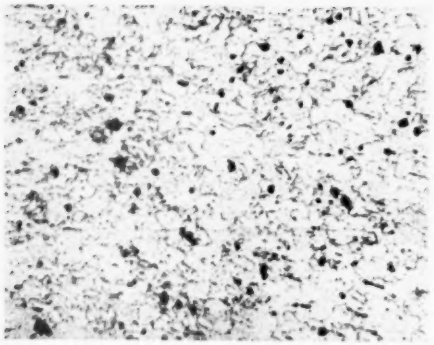


Fig. 25. Plate structure in Mader and Laves alloy. Etched in 10 per cent. acetic acid. (×100)

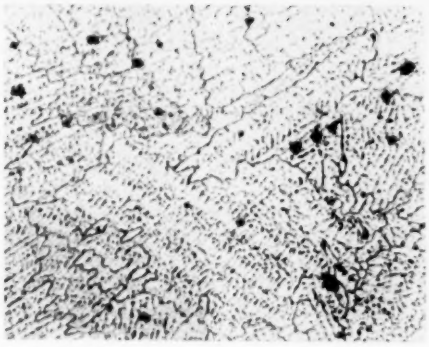


Fig. 26. Weld structure in Mader and Laves alloy. Etched in 10 per cent. acetic acid. (×100)

the limited dimensions of the test weld made in the jig it was not possible to make tensile test specimens from the test weld. Tests were therefore made on specimens cut from small welded panels welded free from restraint. It should be borne in mind, however, that the weld strength values obtained are not necessarily representative of the weld strength of materials welded under complete restraint in the jig. The tensile test results of the materials before welding and after gas and argonarc welding are given in Table V. The specimens were prepared in accordance with British Standard No. 18, and the reinforcement was not removed. (See "Technique for the Gas Welding of Magnesium Alloys," B.W.R.A., T.16, p. 28.) Generally it may be said that the weld strengths of specimens welded by oxy-acetylene and argonarc are similar. The materials may be divided into two groups; group (*a*) consisting of alloys 1 to 4 of Table V having a weld strength of about 7 to 11 tons per sq.in., and group (*b*) of alloys 5 to 10 having a weld strength of about 12 to 18 tons per sq.in. after gas welding. The elongation over the whole range of alloys varies slightly, but lies mainly between about 1·5 to 7 per cent.

CONCLUSIONS

1. Weldability tests under conditions of severe restraint on a series of magnesium-aluminium alloys containing up to 8 per cent. aluminium, and magnesium-aluminium-zinc alloys containing 1 per cent. zinc, with 3 and 6 per cent. aluminium, show that with the argonarc process all the material can be welded without defect. With gas welding the 8 per cent. aluminium alloy and the 6 per cent. alloy with 1 per cent. zinc are liable to junction cracking. There is also a tendency for crater cracking in welds when more than about 5 per cent. aluminium is present or with 6 per cent. aluminium and 1 per cent. zinc. Crater cracking may, however, be eliminated either by feeding the end pool or by terminating in a tack weld.

2. With a magnesium-zinc-zirconium alloy containing 3 per cent. zinc and 0·6 per cent. zirconium the tendency to cracking is only slight with argonarc welding if the gap is kept small, but with gas welding (which is not recommended by the manufacturers) there is severe cracking in the weld metal and in the weld junction. By reducing the zinc content to 1 per cent. and using a special filler rod, the weldability of the zirconium bearing alloy was improved but the use of the special filler rod on the alloy with 3 per cent. zinc should be further investigated.

3. The addition of calcium to magnesium-manganese alloys of the DTD 118 type induces cracking in the weld junction with gas welding, but not with argonarc. The maximum amount of calcium which can be permitted without incurring the danger of cracking in gas welding has not been defined accurately, but the tests show it to be less than 0·09 per cent.

4. The addition of 0·52 per cent. cerium to an alloy of the DTD 118 type induces severe cracking in the weld junction with gas welding, but not with argonarc. The addition of 1·2 per cent. aluminium to the alloy eliminates the tendency to cracking and thus substantiates the claim made by Mader and Laves.

5. In general, junction and crater cracking are less severe with argonarc welding than with gas welding. This is partly due to the use of a smaller gap between the test sheets which is favourable to the use of argonarc welding. When the sheets are close butted, the tendency to cracking is reduced, but with gas welding it is difficult to obtain penetration with close butting.

6. Tensile tests on specimens cut from welded panels (but not welded under severe conditions of restraint) indicate that the alloy containing 7 per cent. of aluminium has the best combination of weldability and weld strength.

ACKNOWLEDGMENTS

Particular acknowledgment is due to Dr. K. Winterton and Mr. C. L. M. Cottrell who participated equally with the authors in the work on weldability which was carried out in the laboratories of the British Welding Research Association.

The mechanical tests were made in the Engineering Division, National Physical Laboratory, except where stated otherwise. Magnesium Elektron Ltd. supplied some of the ingots and also sheet material of alloys Z3Z and ZW1. The circular patch test jig was loaned by Essex Aero Ltd., and determinations of the calcium of some of the alloys were made by B.N.F.M.R.A.

Acknowledgment is also made to Mr. F. C. Dowding, formerly of the Westland Aircraft Co. Ltd., for assistance in the early work, and to Dr. F. A. Fox, late of the B.W.R.A., and to Dr. C. H. M. Jenkins of the National Physical Laboratory for their advice and encouragement.

REFERENCES

1. Tate, A. E. L. *Journ. Inst. Metals*, vol. 78, pp. 71-92 (1950).
2. Winter, D. B. *Magnesium Review and Abstracts*, vol. 6, pp. 39-44 (1946).
3. Singer, A. R. E., and Jennings, P. H. *Journ. Inst. Metals*, pp. 197-212 (1946).
4. Pendleton, J. *Sheet Metal Industries*, pp. 1628-1636 (Aug., 1948).
5. Mader, H., and Laves, F. *Aluminium*, vol. 25, p. 157 (1943). Also R.T.P. translation, No. 2249) by Helledoren, J., issued by M.A.P.

R.78

A NEW DOUBLE-FILLET TEST FOR HOT-CRACKING

The double-fillet test described in this short note was considered by the Weldability Commission at the International Institute of Welding Congress at Oxford in July, 1951.

Interested readers are encouraged to try out the test in its present form, as the experience and results would greatly assist the Association in its task of formulating the most suitable procedures for carrying out the test under workshop conditions.

This presentation should *not* be regarded as the final form of the test. Rather it should be regarded as an outline of the principle of the test. Further work is in progress to extend the scope of the test to cover all gauges of electrodes, and this may entail alteration of the dimensions given.

By E. G. P. HINDS, B.A.

SYNOPSIS

The new test described is for the assessment of hot-cracking susceptibility, and is much more severe than the T-test, which it is intended to replace. In the form described the test has been found useful for research purposes, both for the grading of electrodes and for testing given plate electrode combinations. It is emphasised that this short report is in no sense a specification for a workshop hot-cracking test, though it may well form the basis of such a specification when more experience has been gained.

INTRODUCTION

The new double-fillet test has been developed from the well-known T-test. In the T-test, two fillet welds are laid successively on either side of two plates arranged in the form of an inverted T-joint. The welds are then examined for evidence of cracking.

Although this test is widely used, its application is strictly limited to the detection of really bad electrodes, and the need has therefore arisen for a more severe test which will be certain to reject a doubtful electrode. The new test which has been developed is considerably more severe than the T-test, and furthermore is of variable severity, so enabling any electrode to be graded according to its hot-cracking tendencies.

The two major developments from the T-test are, firstly, that the two welds, the restraining weld and the test weld, are laid nearly simultaneously, and secondly, that the width of the top-member has been increased. Careful work on the type of test assembly shown in Fig. 1, in which the rotation of the top-member produced by the restraining weld was measured by means of a dial gauge, has indicated that the best results are obtained when the second or test weld is begun five seconds after *the start* of the first or restraining weld. This means, of course, that the test requires two welders.

The severity of the test can be altered by varying the width of the top-member. It has been shown that, up to a certain point, the greater the width of the top-member, i.e. the greater the distance between the welds, the greater the severity of the test. For purposes of classifying electrodes, three levels of severity are used, corresponding to widths of the top-member of 1 in., 1½ in. and 2 in. It is suggested that an electrode which produces complete weld cracking with a 1 in. top-member, i.e. at the lowest grade of severity,

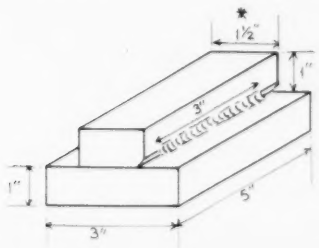


Fig. 1. Diagram of test assembly to show restraining weld.

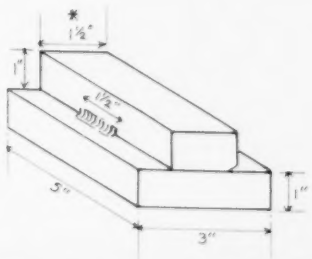


Fig. 2. Diagram of test assembly to show test weld.

* *According to severity required.*

should be rejected in practice. The width of the top-member has not been increased beyond 2 in., as the rotational displacement of the top-member at this distance becomes too great to allow of easy welding.

Two further modifications have been made. Firstly, the restraining weld is made with an austenitic electrode. This enhances the severity of the test, due to the greater coefficient of expansion of austenite, and also produces a fairly constant rotational movement in the top-member without the complicating volume changes arising from the austenite-ferrite change. The molybdenum-containing austenitic electrodes have been found to be the most suitable, as any possibility of hot-cracking in the austenitic weld metal is then minimised.

Secondly, the underside of the top-member is chamfered (see Fig. 3) to prevent root penetration by the restraining weld. Earlier work had shown that variable root penetration by the restraining weld could lead to unreliable results, and it was therefore decided to eliminate this penetration entirely by chamfering the underside edge.

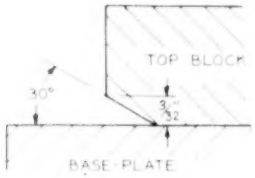


Fig. 3. Enlarged view of chamfered edge (end-on view).

TEST PROCEDURE

The test is carried out on mild steel plate. The carbon content of the plate must lie within the limits 0·18-0·22 per cent., and the sulphur content within the limits 0·02-0·05 per cent. The dimensions of the test-pieces are:

Top-member, 5 in. by 1 in., 1½ in. or 2 in. (1 in. thickness) (according to severity required).
Base plate, 5 in. by 3 in. (1 in. thickness).

One edge of the top-member is chamfered, as in Fig. 3, to prevent root penetration by the restraining weld.

Scale on the upper face of the base plate and the lower face of the top-member is removed by milling or shaping.

Both welds are made with 8 s.w.g. electrodes, the restraining weld being made with an 18/8 stainless steel electrode (preferably containing molybdenum). The restraining weld is 3 in. in length, laid by 4¼ in. of electrode, and the test weld is 1½ in. in length, laid by 2¼ in. of electrode.

Both welds are laid *in the same direction*, the test weld being laid in the *left to right* direction. The restraining weld is started 1 in. from the edge of the plate, and the test weld is started 1½ in. from the edge (see Figs. 1 and 2).

The time interval between the start of the two welds is standardised as follows:

For 1 in. top-member the time interval is 6 secs.
" 1½ " " " " " " 5 "
" 2 " " " " " " 4 "

After completion of the test, the test weld is visually examined for cracking.

INTERPRETATION OF RESULTS AND DISCUSSION

The success of the test is dependent on the quality of the welds, particularly the restraining weld. It is, therefore, essential to control the welding conditions carefully, so that the welds are uniform and of regular fillet size. The current regulators must also be carefully set to give the same current conditions from test to test. The electrodes are tested at the maximum current of the range specified by the manufacturers.

If an electrode produces complete weld cracking in a test, it should be classed as having failed for that particular severity of test. If partial cracking occurs, the electrode should be regarded as a borderline case, and further tests should be carried out to confirm this. If considerable cracking still occurs, then the electrode should be regarded as having failed at that particular severity. Finally, if only slight cracking (up to about ¼ in.) occurs, or if there is no cracking, the electrode is classed as satisfactory for that test. Table I makes this clear.

TABLE TO SHOW THE GRADING OF ELECTRODES

Electrode Grading	Severity Levels	Cracking
1	1 in., 1½ in., 2 in.	No cracking
2	2 in.	Cracking
	1 in., 1½ in.	No cracking
3	2 in., 1½ in.	Cracking
	1 in.	No cracking
4	1 in., 1½ in., 2 in.	Cracking

NOTES: (i) Grade 4 is to be regarded as unsatisfactory for practice.
(ii) Considerable partial cracking is to be treated as complete cracking if this occurs in repeated tests.
(iii) Slight cracking (up to ¼ in.) to be classed with no cracking for purposes of grading.

Printed in England by Lawrence Press Ltd. Henry Road, New Barnet. Herts